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CONSTRUCTION OF EXTENDED LIFE CONTINOUSLY REINFORCED CONCRETE PAVEMENTS AT ATREL

by

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16. Abstract

This report summarizes the design and construction of ten extended life continuously reinforced concrete pavement test sections at the Advanced Transportation, Research, and Engineering Laboratory (ATREL). The ten sections were designed and constructed to determine 1) thickness design curves versus traffic levels, 2) the viability and necessity of 2 layers of reinforcing steel, 3) the design steel content to achieve the desired crack width and spacing, 4) the optimal depth of steel from the Portland cement concrete (PCC) surface, 5) the load transfer efficiency deterioration rate across the cracks, and 6) the effect of uniformly induced crack spacing on the performance of the CRCP.

The soil investigation on the test site along with dynamic cone penetrometer tests were included in this report. Material properties were gathered and documented for each pavement layer. The instrumentation and data acquisition system used to collect early-age and long-term temperature, strain, and deflection measurements were summarized. Falling weight deflectometer test results and initial crack surveys were presented.

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Construction of Extended Life Continuously Reinforced Concrete Pavements at ATREL

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Construction of Extended Life Continuously Reinforced Concrete Pavements at ATREL

I. Project Background

Extended life concrete pavements have design lives of 30 to 40 years, which include more stringent material and construction specifications to assure the design life is achieved. The main concrete option for extended life pavements in Illinois is continuously reinforced concrete pavement (CRCP). Since these pavements will be experiencing significant amounts of traffic over their design lives (> 100 million Equivalent Single Axle Loads (ESALs)), the Illinois Department of Transportation (IDOT) desired full-scale testing to ensure the pavement designs would perform over the intended 30/40-year design life. Full-scale testing would minimize the risk of premature failure of the extended life CRCP and assist in selecting the most appropriate CRCP design.

In December 2001, the University of Illinois received an accelerated pavement test (APT) device called the Advanced Transportation Loading System (ATLaS). The ATLaS is approximately 124 ft. long, 12 ft. high, and 12 ft. wide. The approximate weight of ATLaS is 180 kips. The ATLaS can transmit load to the pavement through a single tire, dual-wheel tire, or an aircraft tire. The load level can vary between 0 and 80 kips. The loading length of the ATLaS is 85 ft. with approximately 65 ft. of constant velocity loading of the wheel. The maximum speed of the wheel carriage is 10 mph. Loading can be either uni- or bi-directional. The wheel load can wander up to 3 feet in the lateral direction to simulate real world traffic conditions. At a 10-mph speed and bi-directional trafficking, the ATLaS can apply approximately 10,000 repetitions per 24-hour day. At a 50-kip wheel load, one pass of the ATLaS wheel carriage at the edge of the concrete pavement is approximately equal to 1,500 ESALs. After only one day of testing, 15 million ESALs can be applied on a 10-inch rigid pavement.

The main purposes of the APT sections, as they relate to extended life CRC pavements, are to determine 1) thickness design curves versus traffic levels, 2) the viability and necessity of 2 layers of reinforcing steel, 3) the design steel content to achieve the desired crack width and spacing, 4) the optimal depth of steel from the Portland cement concrete (PCC) surface, 5) the load transfer efficiency deterioration rate across the cracks, and 6) the effect of uniformly induced crack spacing on the performance of the CRCP. The final design proposal called for 2 500-foot test lanes, with each lane consisting of 5 separate test sections. Figure 1 and Figure 2 present the final test sections for Lanes 1 and 2, respectively.

The CRCP design proposal and a set of construction specifications were given to the university's contracting office to assist them in advertising and awarding the project. At the end of September 2001, the bids were opened and the low-bid contractor, from 2 submitted bids, was selected. The prime contractor for the project was Central Illinois Tile Company (CIT). CIT primarily does work in pavement edge drains, but they also do construction of PCC subdivision roads.

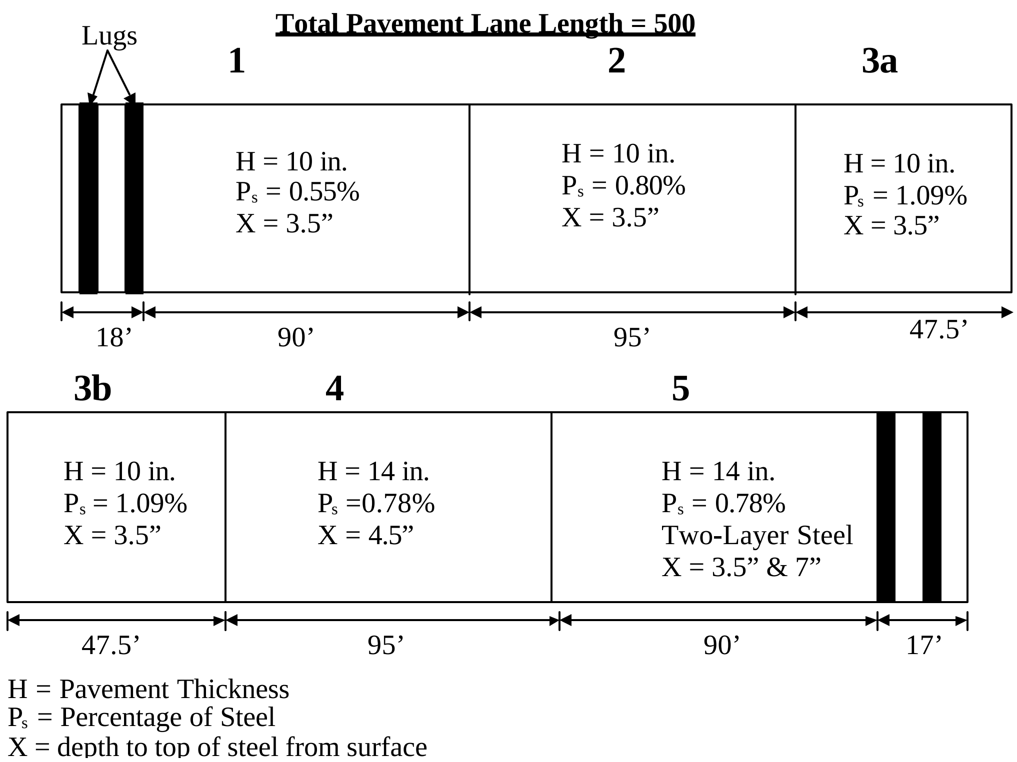
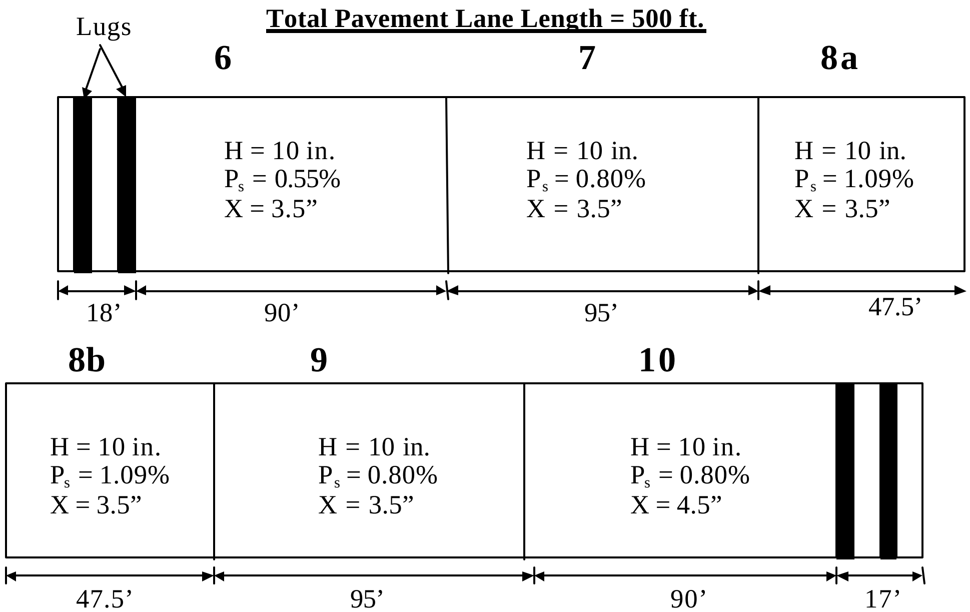


Figure 1. CRC Pavement Lane 1 using traditional CRCP design techniques. (Top View)



H = Pavement Thickness
P_s = Percentage of Steel
X = depth to top of steel from surface

Figure 2. CRC Pavement Lane 2 with induced crack spacing of 2 to 6 feet.

II. Subgrade and Subbase Characterization

During the summer of 2001, university graduate students surveyed the proposed APT site as shown in Figure 3. The boundaries of the APT site (fence) were set at 280 feet by 560 feet. In order to test the end of the test sections with the ATLaS, the total length of the test lanes was limited to 500 feet. The survey also helped to identify the optimal location of the 2 500-foot test lanes to allow for 4 future test lanes adjacent to the CRCP lanes, placement of electrical power poles and lights, as well as to develop a topographic map for establishing the profile of the test sections to facilitate drainage and minimize cut and fill quantities. Figure 4 and Figure 5 show a topographic map at an oblique view and at a plan view, respectively. The stationing from the section starts at zero on the west end of the site and increases easterly.

Figure 3. Photo of Site

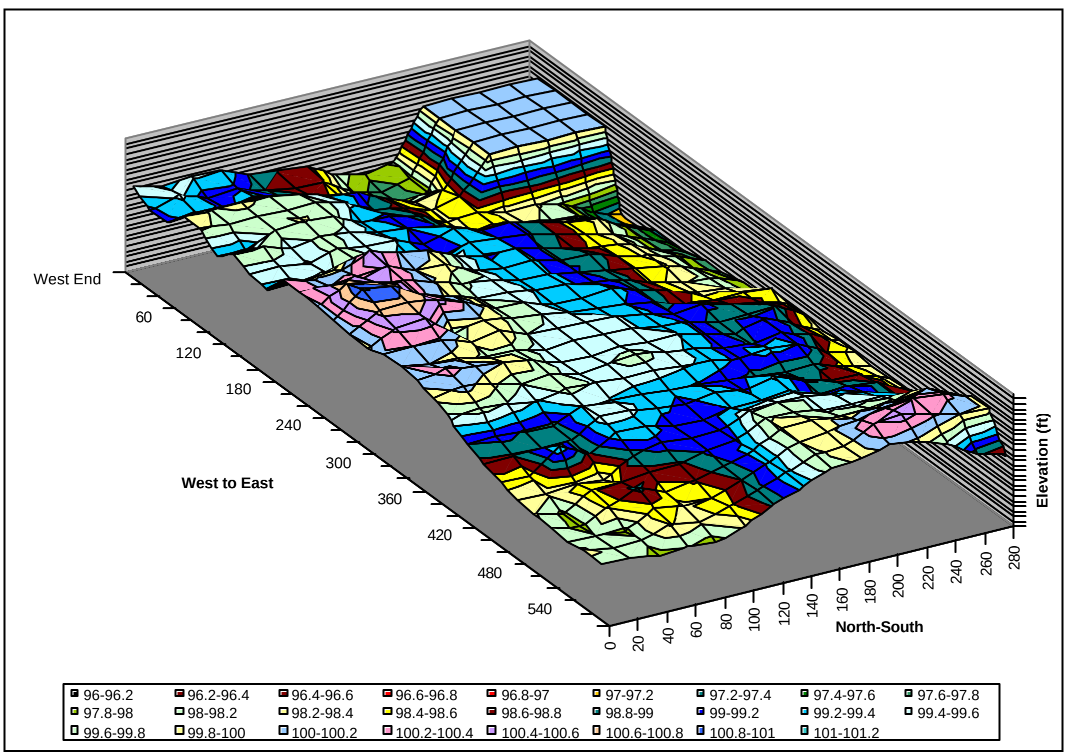


Figure 4. Topographic Map (Oblique View)

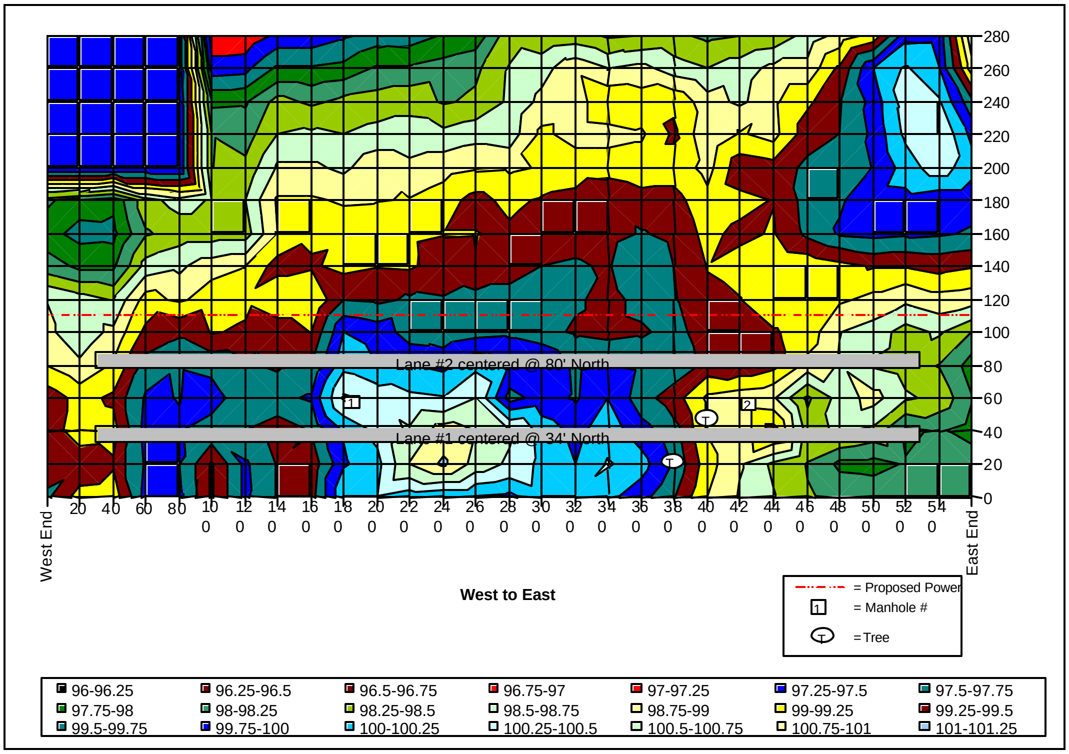


Figure 5. Topographic Map (Plan View)

Once the approximate centerline of each lane was staked, Midwest Engineering Services, Inc. was hired to sample the soil up to a 4-foot depth. A total of 11, 24-inch, split-spoon boring samples were taken along the centerlines of the proposed pavement lanes. Five borings were taken along Lane 1 corresponding to stations 50, 150, 250, 350, and 450 and 6 borings were taken along the centerline of Lane 2 at stations 0, 100, 200, 300, 400, and 500. Several tests were run on the sampled soil from each lane and are further discussed below. The soil types were identified and recorded in the boring logs. Appendix A lists the raw data from each boring.

The results of the boring and laboratory tests suggested there were 3 soil types present on the site. The 2 predominant soil types were a dark brown loess material with a high organic content (Figure 6) and an underlying light brown clayey-silt or Drummer soil (Figure 7). There was also a brown sandy soil present (Figure 8). The western half of the site had the clayey-silt material at the surface, whereas the loess material on the eastern half of the site was up to 4 feet thick.

Figure 6. Photo of Dark Brown Loess

Figure 7. Photo of Light Brown Clayey-Silt

Figure 8. Photo of Sand Seam

Laboratory tests were conducted on the light brown clayey-silt (Drummer soil) taken from boring 2-3, as this was considered the most suitable subgrade material found on site. The tests performed included Atterberg Limits, Immediate Bearing Value (IBV), moisture-density relationship, and clay content. From the Atterberg Limits, the Liquid Limit was found to be 22.5 percent while the Plastic Limit was determined to be 12.8 percent moisture content. The Proctor test produced a relationship between IBV and moisture content as well as a moisture-density relationship as shown in Figure 9 and Figure 10. The moisture-density relationship resulted in an optimum moisture content of 10.8 percent, an in-situ moisture content of 11.5 percent, and a maximum dry density of 124 pcf. The soil had an IBV of approximately 15 at the optimum moisture content. (Note that IBV is similar to California Bearing Ratio (CBR), except IBV uses a 4-inch mold and an unsoaked sample, whereas CBR uses a 6-inch mold and a soaked sample.) Although the IBV value of the material was quite high at its optimum moisture content, it is very sensitive to moisture contents wet of optimum. To further describe this soil, preliminary Dynamic Cone Penetration (DCP) tests conducted by Balmaceda and Hengst (Summer 2001) on the undisturbed soil found the clayey silt material to have a moderate CBR of 8 to 10. Based on hydrometer test results, the clay content of this soil was 6.8 percent. This value is reported as the percent passing the No. 200 sieve in Table 1.

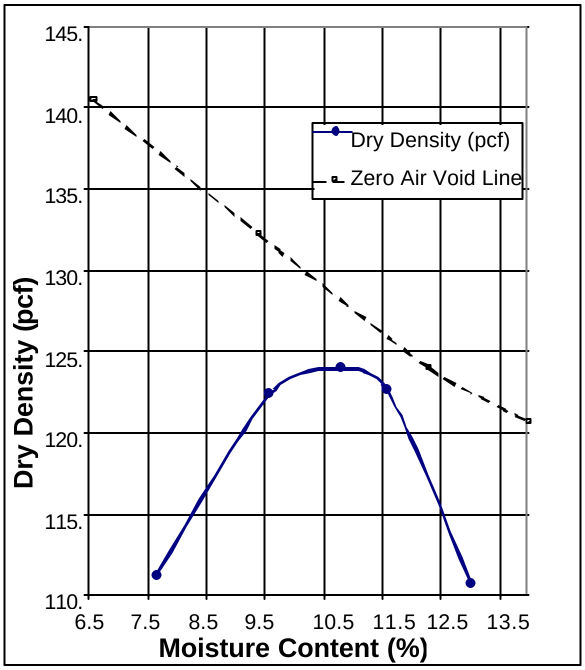


Figure 9. Moisture / Density Relationship for Light Brown Clayey-Silt

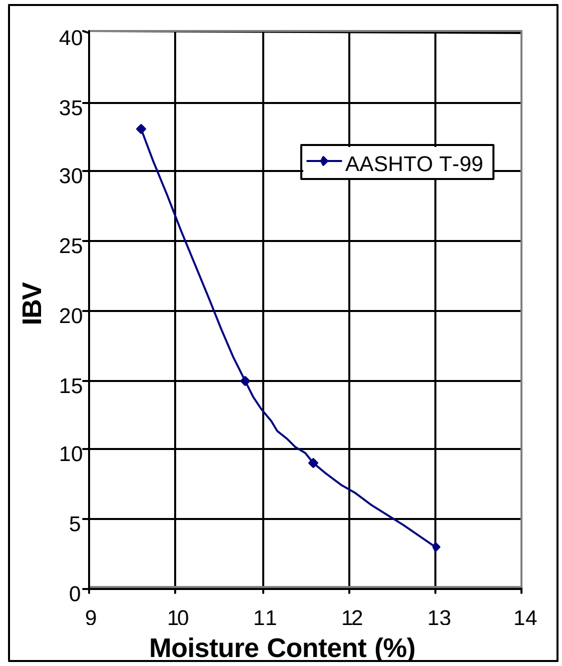


Figure 10. IBV / Moisture Relationship for Light Brown Clayey-Silt

Table 1. Sieve Analysis for Light Brown Clayey-Silt

SIEVE ANALYSIS

PROJECT = ATREL-CRCP

BORING NO. = Lt Brown Sample #2

TOTAL WEIGHT IN GRAMS OF SAMPLE, Ws = 200

SIEVE OPENINGS		U.S. STANDARD SIEVE SIZE OR NUMBER	WEIGHT RETAINED IN GRAMS	PERCENT RETAINED		PERCENT FINER BY WEIGHT	
INCHES	MILLIMETERS			PARTIAL	TOTAL		
0.187	4.76	No. 4	3.95		2.0%		95.5%
0.0079	2	No. 10	15.04		7.5%		88.0%
0.0023	0.59	No. 30	24.52		12.3%		75.7%
0.0117	0.297	No. 50	75.52		37.8%		38.0%
0.0059	0.149	No. 100	39.84		19.9%		18.1%
0.0029	0.074	No. 200	22.51		11.3%		6.8%
		Pan	13.62		6.8%		0.0%

From the laboratory test results, the light brown clayey-silt was classified as a ML following the Unified Soil Classification System. The soil can be identified in the boring logs as a "light brown clayey-silt". This soil is an A-2-4 according to the AASHTO Classification System. The soil is further described as a Drummer soil, or more specifically a Drummer silt loam when considering the lab results in comparison to the published Soil Survey of Champaign County.

Atterberg Limits, IBV, and moisture-density relationship were also determined for the dark brown loess. From the Atterberg Limits, the plastic limit and liquid limit on the dark brown loess were 22.9 and 50 percent, respectively. From the moisture-density relationship shown in Figure 11, the optimum moisture content was determined to be 19.0 percent and maximum dry density of 106 pcf with an in-situ moisture content of 21.0 percent. As found in Figure 12, the soil had an IBV of 13 at the optimum moisture content. The preliminary DCP tests conducted during the summer of 2001 on the undisturbed soil determined CBR values to be 4 or less. According to the Unified Soil Classification System, this soil was also considered ML and can be identified in the soil boring logs as a "dark-brown loess". There was no sieve analysis conducted on this soil. Without a grain size distribution, the soil cannot technically be classified by the AASHTO classification system.

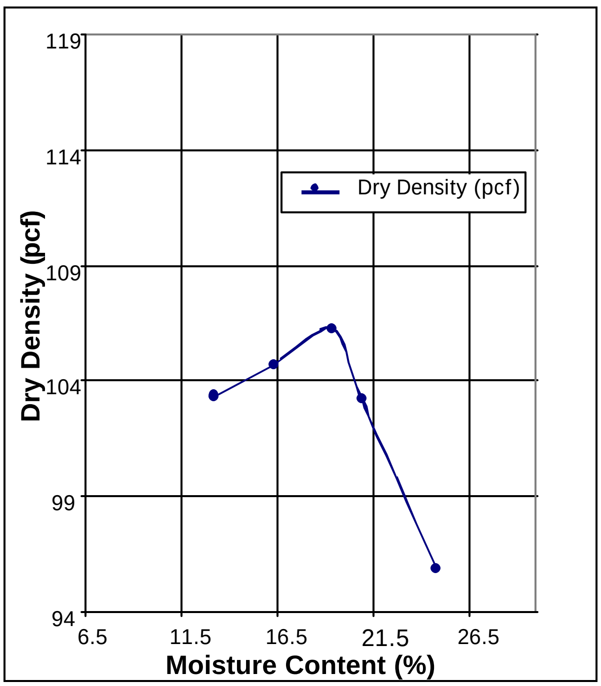


Figure 11. Moisture / Density Relationship for Dark Brown Loess

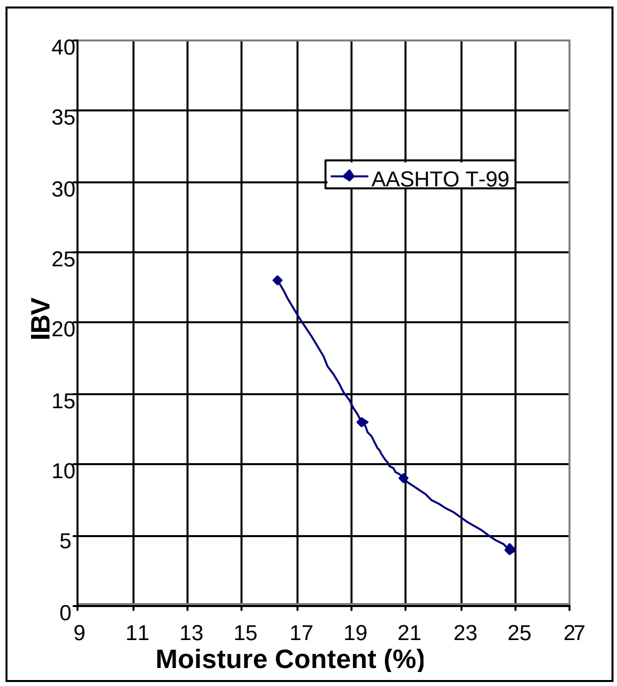


Figure 12. IBV / Moisture Relationship for Dark Brown Loess

There were no laboratory tests conducted on the brown sandy soil since it was not found to be predominant at the test site. Its Unified Soil Classification is SC. The AASHTO classification cannot be determined without additional laboratory tests. It is identified in the soil boring logs as a “sandy clay”.

Based on the soil boring, DCP data, Proctor, and Atterberg tests, and the topography map, the final profile of the test lanes was determined to minimize cut and fill and promote adequate drainage of the site. Cut and fill calculations were based on the profiles of Lane 1 and Lane 2 that are shown in Figure 13 and Figure 14, respectively. These figures show the natural topography along the 500-foot sections, the change in soil layers from the dark brown loess to the light brown clayey silt, the final cut depth, and the final pavement elevation. In order to provide more uniformity in the test section, approximately 2 feet of loess material was removed from the surface of the eastern half of the test site. The final pavement elevations at the western half of both test lanes have a zero gradient, while there is a 0.5 percent slope on the eastern half of both test lanes. This was done to minimize the amount of fill required, after loess material was removed, as well as to enhance the positive drainage to the southeast.

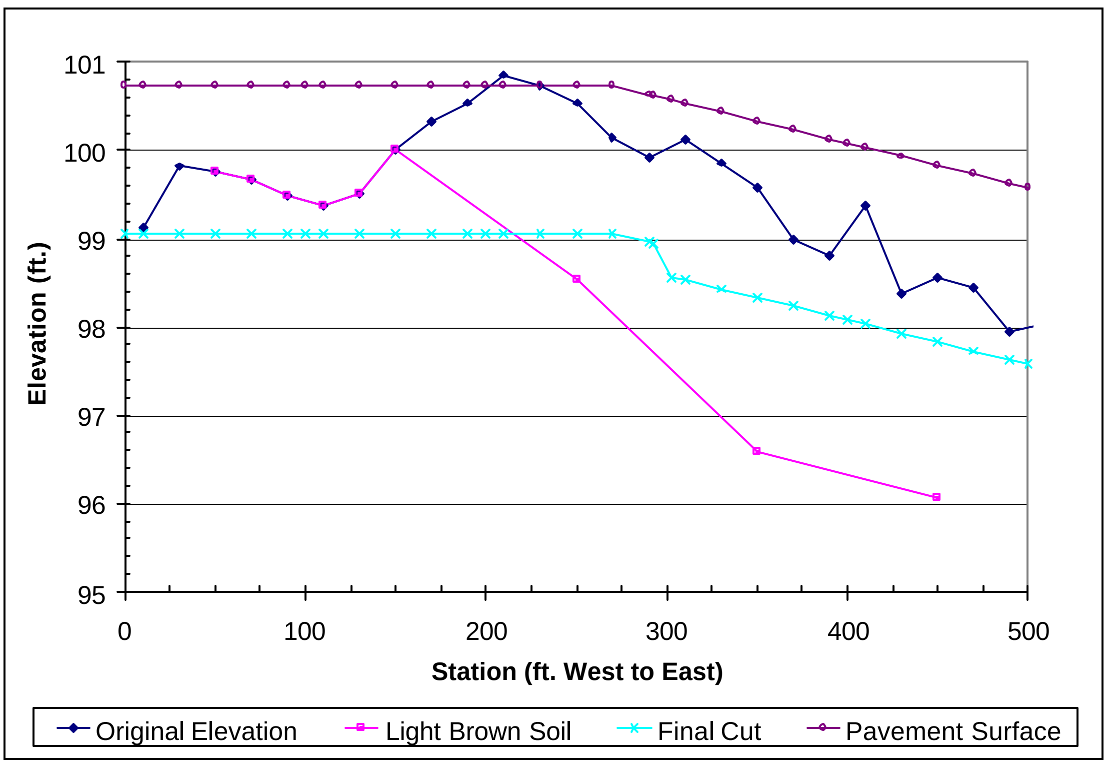


Figure 13. Lane 1 Profile

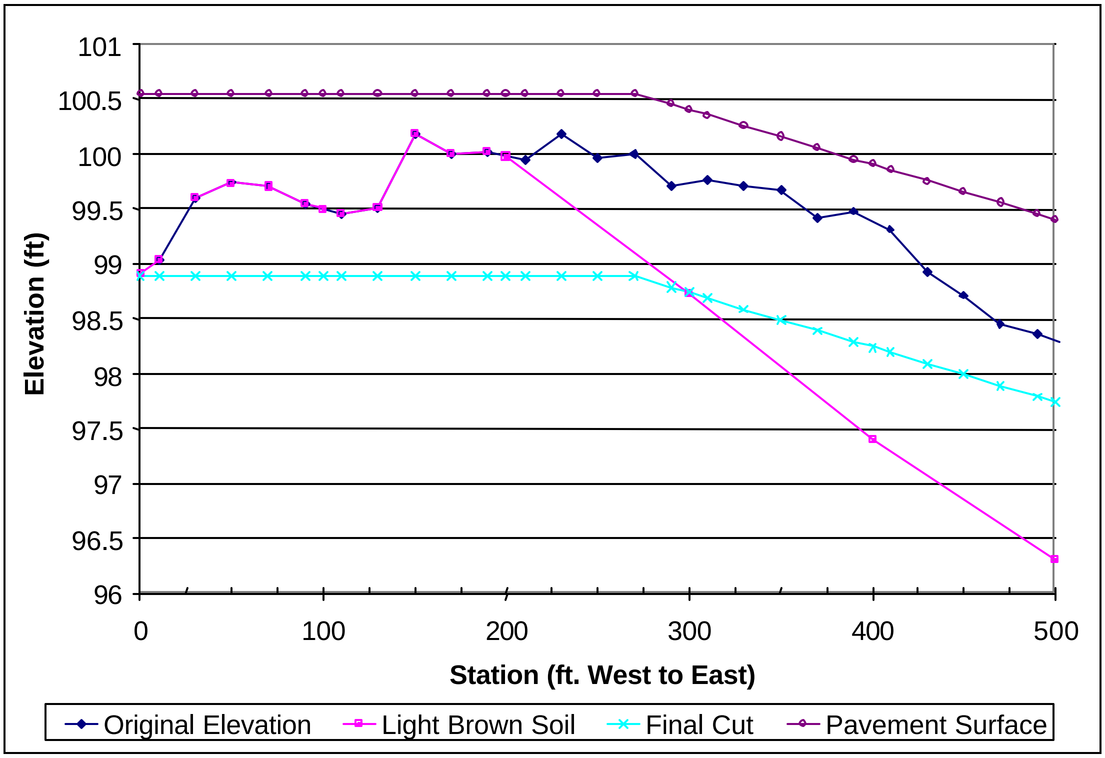


Figure 14. Lane 2 Profile

The contractor began working on the site in the middle of October 2001.
The contractor used a combination of an excavator, dozer, trimmer, and vibratory tamping foot to prepare the subgrade to the required density. Figures 15 A - E show the equipment used by the contractor to prepare the subgrade.

Several punch tubes were collected to verify the density of the in-situ soil versus the established Proctor curves. The relative density ranged from 91 to 108 percent of AASHTO T-99 and the data is presented in Table 2. After the contractor had compacted the subgrade in both lanes, several soft spots were noted where water was seeping to the surface (Figure 16). This was the same area where a sand seam was found and may have been the location of an old creek bed. The contractor recommended undercutting several feet and backfilling it with 3-inch minus crushed stone. The University of Illinois proceeded with this recommendation, since adequate compaction of the aggregate subbase and bituminous aggregate mixture (BAM) would be difficult in these soft spots. The aggregate subbase thicknesses in these areas were estimated from the DCP data and graphed in Figure 17 to help indicate the locations that were undercut. Figures 18 A - D show the excavation and backfilling of the soft spots with 3-inch minus stone.

Figures 15 A - E. Contractor Subgrade Cut, Fill, and Compacting Equipment

Table 2. Field Density of Fill

	Sta.	Depth (inches)	Wet Density (pcf)	Dry Density (pcf)	% Density (of 124 pcf)
Lane 2	25	3.86	148	133	108
	100	3.94	145	127	102
	175	5.71	142	126	102
	250	6.02	134	113	91
	325	4.41	137	120	97
	400	1.77	136	118	95
Lane 1	250	5.28	137	117	95
	350	5.83	136	114	92
	450	5.04	136	118	95

Figure 16. Soft Spots in Subgrade

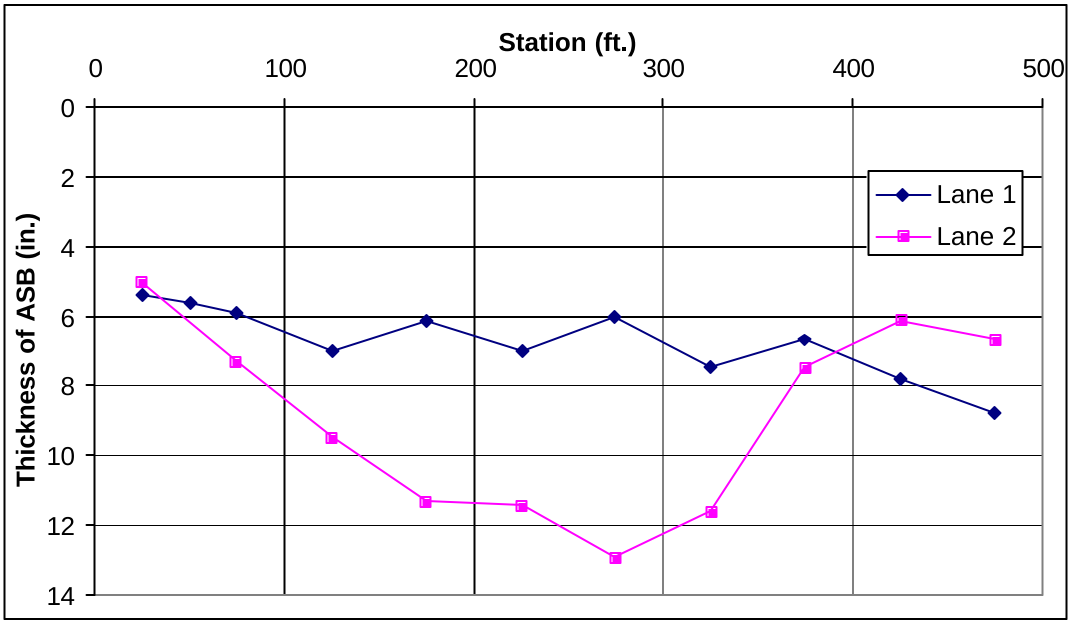


Figure 17. ASB Thickness per Station

Figures 18 A - D. Excavation and Backfill with 3–In. Minus Stone

Before placement of the 6-inch aggregate subbase (ASB) layer, an 8-ounce per square yard non-woven geotextile was placed as a separator layer between the relatively low strength subgrade and ASB as shown in Figures 19 A - C. The ASB material was a CA6 gradation meeting IDOT specification. The material was delivered from Fairmont, IL (Material Service Corporation). The CA6 was placed with a dozer and compacted with a small vibratory roller as shown in Figures 20 A – C. There were no direct density tests conducted on the ASB.

Dynamic Cone Penetrometer tests were conducted on 50-foot centers to determine the correlated CBR of the ASB and subgrade soil. Summaries of the correlated CBR results for the undisturbed soil, the aggregate subbase material, and the compacted subgrade soil are listed in Table 3 by location along the proposed lanes. Figure 21 and Figure 22 offer a graphical view of the soil strength for comparison purposes. As noted above in the discussion of the soil borings and evident from the CBR results and virgin soil tests, the western half of the test area possessed better soil strength with higher CBR values than the eastern half. The eastern half of the project contained a deeper concentration of black loess soil than the western half, requiring additional cut and fill to increase the soil strength in the eastern region. Table 4 and Figure 17 estimate the thickness of the ASB at each station. This approximate depth was determined by using the change in correlated CBR with depth as an indicator of a material type change. The location and depth of undercut sections (in the subgrade) is also apparent by noting the ASB thickness.

Figures 19 A – C. Non-woven Fabric

Figures 20 A - C. CA6 Placement and Compaction

Table 3. Average CBR Values

Virgin Soil From top of existing soil to 40" depth	Sta	0	50	100	150	200	250	300	350	400	450	500
	Lane 1	28	14	26	20	18	9	5	10	6	7	5
	Lane 2	31	32	14	14	18	7	12	10	11	6	6
ASB Layer From 0" depth to bottom of ASB layer	Sta	25	50	75	125	175	225	275	325	375	425	475
	Lane 1	21	28	25	27	21	39	43	42	30	36	43
	Lane 2	20	-	15	28	29	34	37	42	31	45	43
Subgrade Soil From bottom of ASB layer to 30" depth	Sta	25	50	76	125	175	225	275	325	375	425	475
	Lane 1	5	9	4	7	7	6	9	5	6	7	6
	Lane 2	13	-	4	6	6	4	3	10	5	5	5

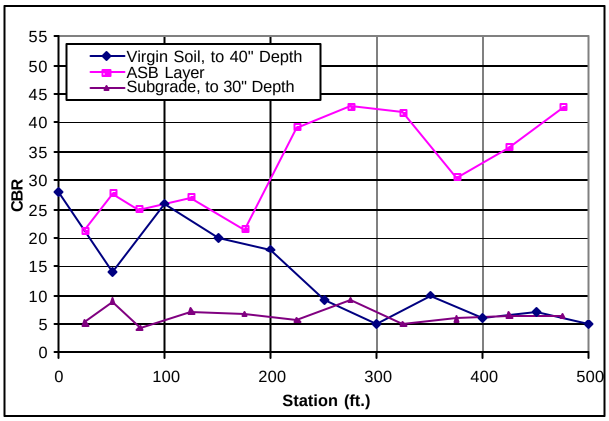


Figure 21. Lane 1 Average CBR

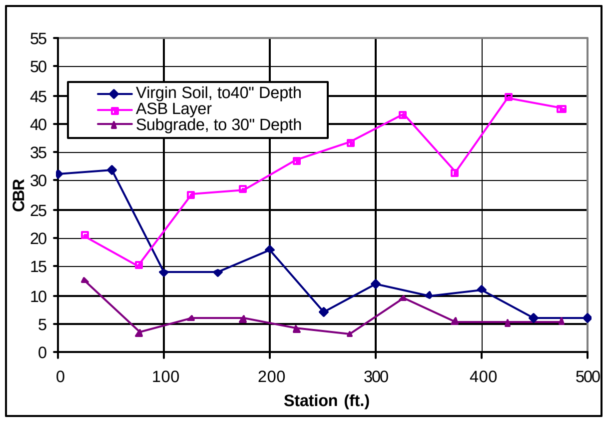


Figure 22. Lane 2 Average CBR

Table 4. Inches of ASB per Station

Sta	25	50	75	125	175	225	275	325	375	425	475
Lane 1	5.4	5.6	5.9	7.0	6.1	7.0	6.0	7.5	6.7	7.8	8.8
Lane 2	5.0	-	7.3	9.5	11.3	11.4	12.9	11.6	7.5	6.1	6.7

During accelerated pavement testing, the strength/stiffness of the individual section's subgrade will be determined with some initial light-load level tests. Complete soil uniformity and homogeneity along the test CRC sections was not as important as uniformity in compaction and density of the soil and ASB.

III. Bituminous Aggregate Mixture

The construction of the bituminous aggregate mixture (BAM) base was completed on November 6, 2001. Champaign Asphalt, Inc. was subcontracted to place the BAM on both test lanes. An existing IDOT approved BAM mix design (N30 mix, PG64-22) was selected for the test section. This was based on previous SUPERPAVE work for this particular mix on another project. The BAM base was placed in 1 lift at a 4-inch depth. The entire 1000 feet of BAM was paved in approximately 6 hours. The contractor used a conventional asphalt paver with tandem dump trucks supplying the hot mix asphalt concrete (AC). The contractor utilized a vibratory breakdown roller and then a static finish roller. Figures 23 A - B demonstrate the construction of the BAM. The density of the mat was checked by Champaign Asphalt's quality control/quality assurance (QC/QA) inspector. The QC/QA inspector used a nuclear density gage for the density check of the BAM. The results showed that the BAM had a minimum density of 94 percent and a maximum density of 98 percent. Several days after the BAM placement, IDOT personnel conducted Falling Weight Deflectometer (FWD) testing on the BAM/ASB/subgrade combination as shown in Figures 24 A - B.

Figures 23 A - B. Construction of BAM on Lane 1

Figures 24 A - B. FWD Testing on BAM

From the FWD testing, the surface deflection of the BAM was measured. The results were normalized to a 9,000-lb load and can be seen in Figure 25. The average deflection was approximately 42 mils with a standard deviation of approximately 8 mils. Overall, the deflections were lower at the eastern end, which correlated with the higher final CBR values for the ASB and the subgrade at that end of the lane, assuming the BAM had a uniform thickness throughout. The BAM stiffness is expected to increase due to aging of the asphalt cement.

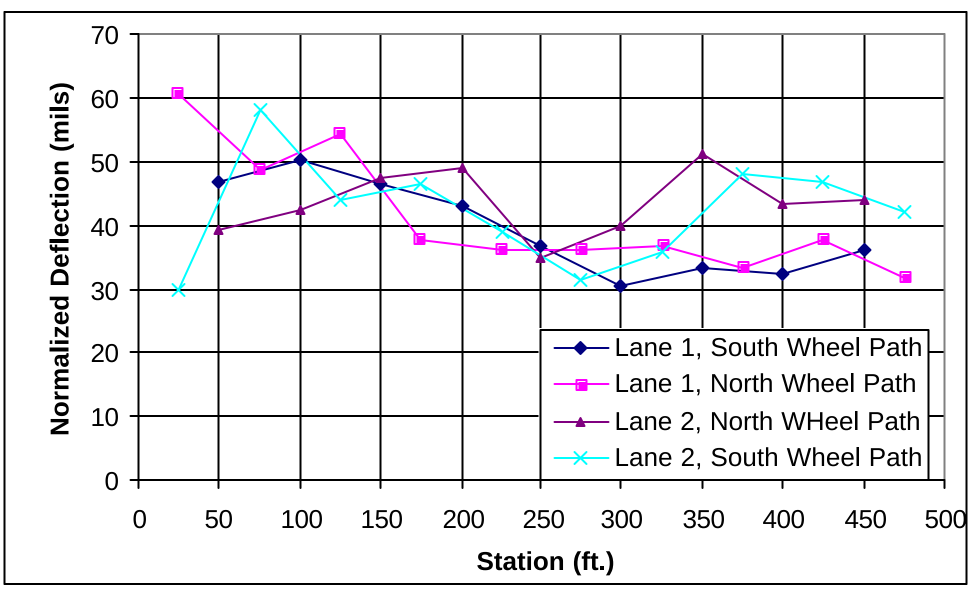


Figure 25. FWD Deflections Normalized to a 9000 lb. Weight – Top of BAM Layer

Also, the moduli for both the BAM and the subgrade were backcalculated from the FWD test results using algorithms for conventional flexible (AC over granular) sections developed by Thompson (1989).

$$\text{Log}(E_{AC}) = 1.48 + 1.76 * \text{Log}(\text{Area} / D0) + 0.26 * (\text{Area} / T_{AC})$$

$$\text{Log}(E_{Ri}) = 1.51 - 1.19 * D3 + 0.27 * \text{Log}(D3)$$

Where Area (inches) = 6 * [D0 + 2D1 + 2D2 + D3] / D0
D0 = deflection directly under the center of the loading plate
D1 = deflection 12 inches from the center of loading plate
D2 = deflection 24 inches from the center of loading plate
D3 = deflection 36 inches from the center of loading plate
T_{AC} = AC thickness (BAM = 4 inches)

The results are available in Figure 26 and Figure 27 with detailed results found in Appendix B. The average modulus of the BAM layer was backcalculated to be 250 ksi with a standard deviation of approximately 100 ksi for a pavement temperature of 80 degrees Fahrenheit. The average subgrade modulus was 2 ksi with the results indicating a modulus of closer to 1.5 ksi toward the eastern end of the project. The E_{Ri} values were highest towards the center of the paved lane, while they were very low at the western end of Lane 1, as indicated in Figure 27.

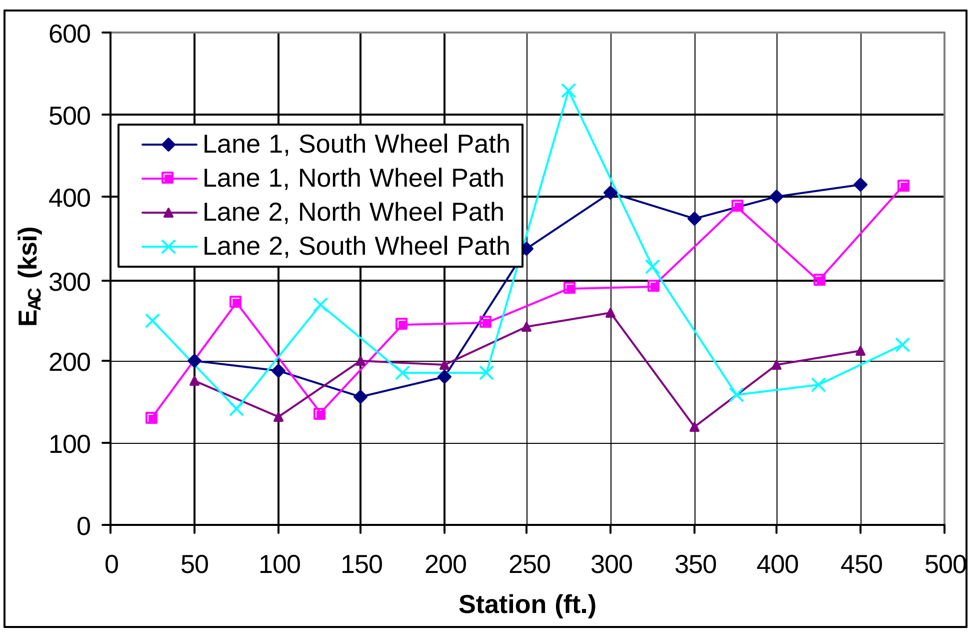


Figure 26. E_{AC} of BAM Layer Backcalculated from FWD Results

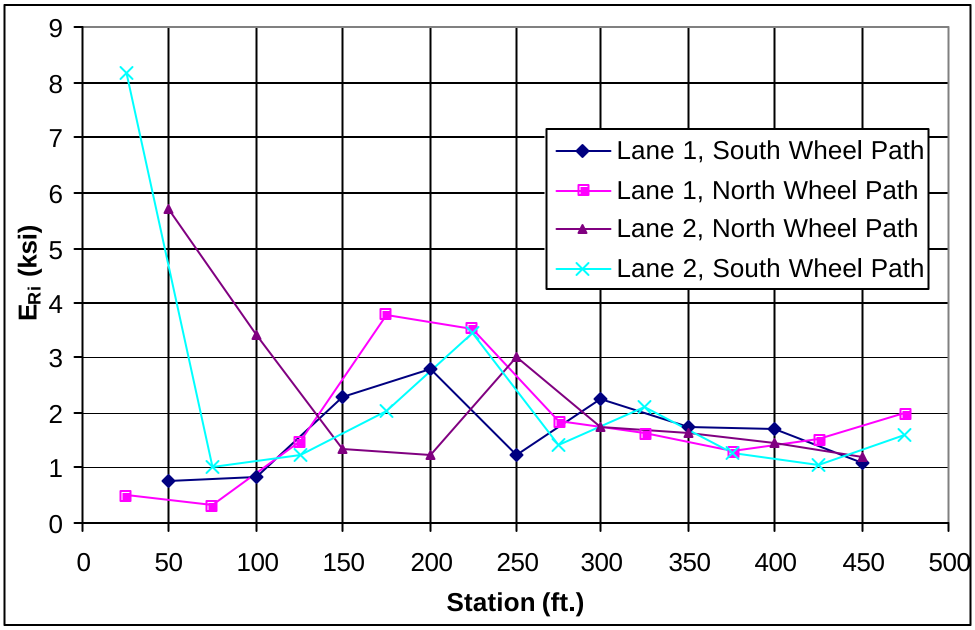


Figure 27. E_{Ri} Backcalculated from FWD Results

IV. Steel Reinforcement

Early in the design phase, the Concrete Reinforcing Steel Institute (CRSI) had indicated that one of their member companies could supply the University of Illinois with the epoxy-coated steel, free of charge. Ultimately, Toltec Steel Services/ABC Coating of Kankakee, IL supplied the University of Illinois with approximately 35 tons of epoxy-coated bars to help construct the CRCP test sections. On October 22, 2001, the epoxy-coated reinforcement bars were delivered to the test site in Rantoul, on 2 flat bed semi-trailers. The donated bars were used in the longitudinal steel, transverse chairs, and the lug systems. Toltec Steel Services/ABC Coating also supplied the University of Illinois with plastic chairs for use in supporting the longitudinal bars. The University's experience with the plastic chairs was not favorable. The plastic chairs were found to be quite time consuming in terms of the fabrication and also in moving the chairs out to the site. Furthermore, during longitudinal steel placement, lateral spacing of the steel was difficult, since the transverse bars did not have pre-fabricated clips for placing the longitudinal steel at the correct lateral position.

Prior to placement of the longitudinal steel, a detailed placement table was created in order to avoid field construction errors. Due to the high labor costs associated with placement of steel and the complexity of the placement locations, the University of Illinois team decided to use internal labor (students and staff) to complete the 35 tons of steel placement as shown in Figure 28.

Figure 28. Students Placing Rebar

A general description of the design steel placement is listed in Table 5. The transition between the different steel contents was done by keeping the number of bars constant and then changing the bar size to increase the steel content at the same bar spacing. Since the bar size changed every 95 feet, splicing was necessary. A total of 4 splicing zones between sections were necessary for each 500-foot lane. Each splice zone was approximately 10 feet long, leaving 85 feet of pavement with a uniform reinforcement configuration per section with a total of 5 sections per lane. The splicing was a modified version of Lap Detail I of IDOT Highway Standard 421001. The modification consisted of 3 separate planes over a 10-foot width (1/3 of bars spliced per plane). Splicing of the bars was completed with a minimum of 2 separate wire ties. Figure 29 is a typical splice detail for all the sections.

Table 5. Reinforcement Bar Locations (Design)

	Section	Station	Bar No.	Spacing, Horizontal (Vertical)	Depth from PCC Surface	Percent Steel	Pavement Thickness
Lane 1	1	18-108	#5	5.5”	3.5”	0.55%	10”
	2	108-203	#6	5.5”	3.5”	0.80%	10”
	3	203-298	#7	5.5”	3.5”	1.09%	10”
	4	298-393	#7	5.5”	4.5”	0.78%	14”
	5	393-483	#7	11” (3.5”)	3.5”, 7”	0.78%	14”
Lane 2	6	18-108	#5	5.5”	3.5”	0.55%	10”
	7	108-203	#6	5.5”	3.5”	0.80%	10”
	8	203-298	#7	5.5”	3.5”	1.09%	10”
	9	298-393	#6	5.5”	3.5”	0.80%	10”
	10	393-483	#6	5.5”	4.5”	0.80%	10”

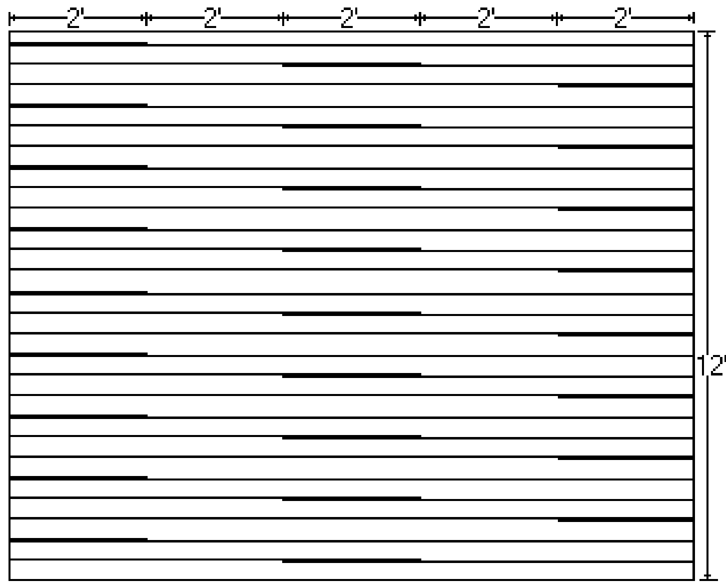


Figure 29. Splicing Detail

A total of 26 bars were placed across each section. Epoxy-coated longitudinal steel bars were supported every 4 feet on transverse steel chairs made of #4 bars. The placement strategy started with laying out the chairs and #4 transverse bars at 4-foot centers. The 26 longitudinal steel bars were then moved into place across the pavement width. After all longitudinal steel was placed on the lane, the tying of the steel to the chairs commenced. Several wood templates were made to ensure the bars were equally spaced at 5.5 inches on centers as indicated in Figures 30 A - B. Every bar was tied to the transverse chairs to promote stability in the steel mat. In the splice zones, at least 2 steel ties were used to hold the longitudinal bars in place. The longitudinal steel was laterally spaced correctly for the majority of the bars, but the outer bars on both sides of the lane were sometimes not spaced a full 5.5 inches apart due to the insufficient length of the transverse chair support. There were 2 layers of bars in Lane 1, Section 5 that were placed at 11-inch horizontal spacing, but were staggered so that there was a 5.5-inch horizontal spacing between each bar, with an 11-inch spacing between any 2 bars in the same layer.

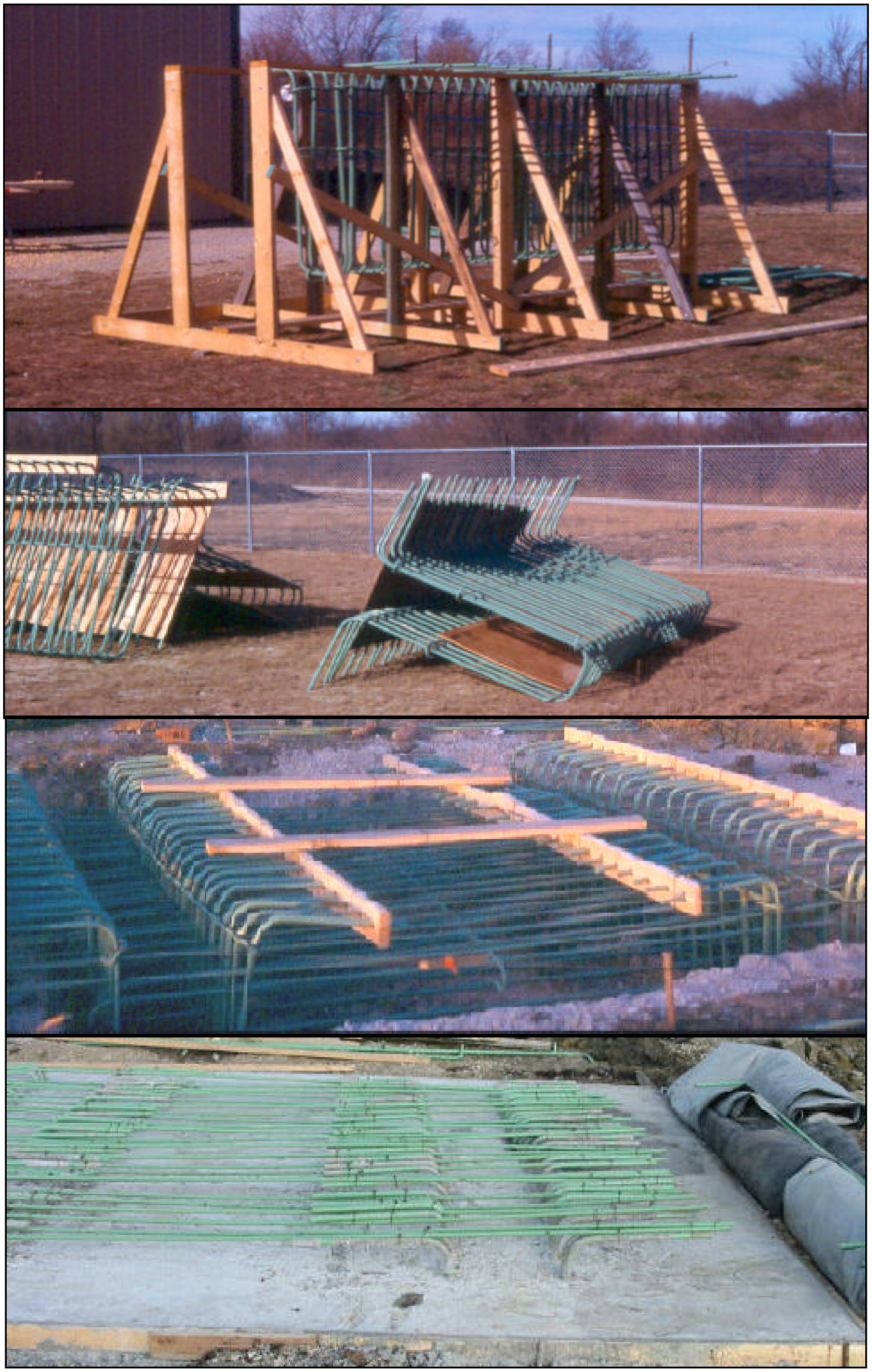
Figures 30 A - B. Wood Templates Used to Space Bars

The lugs design followed IDOT's guidelines with minor adjustments. The project space limitations required the lug spacing to be shorter than typical IDOT specification. The lug system extends 17 feet with 2 continuous transverse columns across the pavement width that protrude 4 feet into the subgrade. These 2 columns were connected together by an 18-inch reinforced concrete slab, adding stiffness to the system and preventing rotation of the tops of the lugs. The individual lug systems were initially constructed on a wood frame (Figures 31 A - D) to make it easier to place and tie the steel. After the lug cage was assembled, the contractor moved the cage into place with an excavator. All 8 of the lug cages were fabricated in the wood frame. After the lug cages were placed in the ground, longitudinal steel was used to tie the 2 lug cages together at the end of both lanes. After the lug cages were tied together, concrete (approximately 4 feet deep) was cast around the steel. The main challenge of the lug system was tying the longitudinal steel from the pavement into the protruding lug bars. It was difficult to maintain accurate spacing between the protruding bars on the lugs, due to the overall weight of the lug system combined with moving the assembly into place. However, the main purpose of the lugs was to fasten the continuous longitudinal bars to a rigid support to prevent the total CRCP section from contracting.

Steel bar samples were taken to IDOT's laboratory in Springfield to verify the yield strength of the steel and thickness of epoxy coating. All bars supplied to IDOT for this testing passed the minimum requirements for yield strength and epoxy-coating thickness, as shown in Table 6.

Table 6. IDOT Coupon Test Results from Steel

		Yield Strength psi (kPa)	Ultimate Strength psi (kPa)	Elongation, %	Bend Test Pass / Fail
Specification (min)		60,000 (400,000)	90,000 (600,000)		
Test #	A1	61,015 (420,682)	96,874 (667,922)	12	Pass
	A2	63,387 (437,040)	102,871 (709,270)	13	Pass
	A3	62,492 (430,870)	101,658 (700,908)	13	Pass
	A4	64,182 (442,522)	105,893 (730,106)	13	Pass
	B1	61,915 (426,891)	96,024 (662,062)	12	Pass
	B2	62,032 (427,695)	100,290 (691,475)	14	Pass
	B3	60,540 (417,412)	101,544 (700,123)	16	Pass
	B4	64,716 (446,202)	105,726 (728,956)	14	Pass



Figures 31 A - D. Lugs

V. Instrumentation and Data Logging System

A variety of sensors was installed in this test section in order to monitor the early-age and repeated load performance of the CRC pavement and to identify differences in pavement responses between test sections. The set of instruments that was used to collect data on the project can be mainly categorized in 2 systems: static and dynamic. The static system corresponds to all the sensors intended to collect data related to the early age responses due to concrete material hydration and shrinkage coupled with the local environmental conditions during construction. The dynamic sensors record the pavement responses induced by traffic load from the ATLaS. These 2 systems are installed on all sections and consist of instruments on the surface of the CRCP along with embedded sensors. The static and dynamic systems are independently controlled, each having their own data-logger. The static system has been operating on all the sections since the start of concrete placement in early December 2001. The dynamic system will only run on the section that the ATLaS is trafficking. The static system is composed of strain gages in the concrete, strain gages on the reinforcement bars, thermocouples, and Linear Variable Differential Transformers (LVDTs) . The dynamic system also includes concrete strain gages, thermocouples, and LVDTs. The main difference between the 2 systems is in the frequency of data sampling.

STATIC AND DYNAMIC INSTRUMENTATION SYSTEMS

Static sensors

The static sensors collect longitudinal deformations in the concrete and vertical and horizontal displacements at the concrete near the cracks, caused by contraction due to concrete shrinkage and temperature loss. The longitudinal deformations are measured by strain gages embedded in the concrete and by strain gages attached to reinforcement bars. The displacements at the visual cracks are sampled by LVDTs. The static sensor information is collected by 2 independent dataloggers located next to each lane.

The following is a description of each type of sensor utilized. Detailed technical information is presented in Appendix C.

Concrete strain gages: The strain gages used are embedment gages specially designed for measuring mechanical strains inside concrete structures. According to the manufacturer, Micro-Measurements, the rugged outer body of polymer concrete resists mechanical damage during pouring, and provides protection from moisture and corrosive attack. The sensors are 5 inches long, by 0.7 inch wide, by 0.4 inch high, with an active gage length of 4 inches. These gages were placed parallel to the longitudinal axis of the CRC pavement, and were mounted on chairs to keep them in position at the desired depth.

Reinforcement strain gages: These sensors are general-purpose strain gages (foil gages). Each gage is 0.25 inch long by 0.12 inch wide, with overall dimensions of 0.415 inch by 0.12 inch. The strain gages were epoxied to the surface of the reinforcement steel. The reinforcement strain gages also come from Micro-Measurements.

LVDTs: Two similar types of LVDTs are being used. Both types include hermetically sealed stainless steel shells and are specifically designed for use in wet and/or dirty environments. The differences between them is that the horizontal LVDTs have a spring-loaded probe and a measurement range of $\pm$0.125 inch. The core in the vertical LVDTs is free and has a measurement range of $\pm$0.250 inch. The manufacturer is MacroSensors.

Thermocouples: Type T (Copper-Constantan) thermocouples were used. Wires with 2 different gages were needed because of the potential loss of signal in long lead wires. The farthest sections from the dataloggers used AWG 20, whereas AWG 24 was used in the 3 center sections. The supplier of the thermocouple wires was Omega Engineering.

Dynamic sensors

The sensors in the dynamic system are the following:

Concrete dynamic strain gages: The type of gage used is specially designed to measure strain in concrete under a dynamic loading. The gage is sealed between thin resin plates and has dimensions of 5 inches long by 0.5 inch wide by 0.2 inch thick. The gage length is 2.36 inches . The manufacturer is Tokyo Sokki Kenkyujo CO.

LVDTs: The LVDTs used with the dynamic system are the same type used with the static system, intended to measure vertical and horizontal movement at the cracks.

Thermocouples: The dynamic system will employ the same Type T thermocouples as the static system (24 AWG).

Cable/Wire

The cables used for the static strain gages (steel and concrete embedment gages) are connected to the data acquisition system using 3-wire conductor. When 3-wire conductor is used instead of 2-wire, the leadwire resistance effects are virtually eliminated. However, the use of 2-wire conductor is acceptable for dynamic load applications. Shielded, low voltage cable with 3, 24 AWG conductors, and PVC jacket was employed for the strain gages. The same type of cables were used for the LVDTs, but with 4 wires. In total, almost 14,000 lineal feet of 3-wire cable, 6,500 feet of 4-wire cable, and 700 feet of 2-wire cable were used for this project.

Datalogging Systems

Two datalogger units were used for the collection of static instrumentation data, one for each lane. Both static sensor datalogging units and the datalogger for the weather station were identical. The datalogger model was CR10X manufactured by Campbell Scientific Inc. A CR10X unit is a fully programmable module with 128Kb for data storage. The storage capacity allows more than 60,000 data values to remain in the datalogger's memory between downloads. The unit consists of a measurement and control module, with a detachable wiring panel. The wiring panel contains a 9-pin serial I/O port used when communicating with the datalogger and provides terminals for connecting sensor, control, and power leads to the CR10X.

The units were programmed using the PC208W Datalogger Support Software. This software enables the user to interact with Campbell Scientific's dataloggers using a PC. It is also utilized to monitor real-time data and to retrieve stored data. The programs were specifically written to collect data from the strain gages and thermocouples at specified intervals, then to process the raw data into the desired units, and finally to store the resulting information in the appropriate format. Additional information on the programs can be found in Appendix D.

Multiplexer units were placed between the datalogger and the sensors to increase the amount of available channels for data collection in both lanes. For the thermocouples, an AM25T Solid State Multiplexer was used to increase the total thermocouple channels to 25. For the strain gages, 3 AM16/32 Relay Mutiplexers were employed to accommodate 48 strain gage channels (16 channels each, plus 2 direct connections to the datalogger, therefore 50 strain gages total are handled). A PS12LA module supplies the power for datalogger and sensors. This module consists of a 12V battery and a charging regulator. Finally a NL100/105 Network Link Interface module was installed with each of the dataloggers to allow communication using an Ethernet 10 Base-T link. This Ethernet link has not been utilized to date due to the inability to connect up with the University of Illinois campus network. Data transmittal is currently being done manually via a laptop computer and the 9-pin I/O port.

All the data acquisition system electronics were placed in protective enclosures that guard them from dust, water, sunlight, and environmental pollutants. These enclosures are made out of fiberglass-polyester and were attached vertically to poles located about the midpoint of each lane and offset approximately 15 feet from the edge of slab.

A schematic of the components present in the datalogging system is shown in Figure 32.

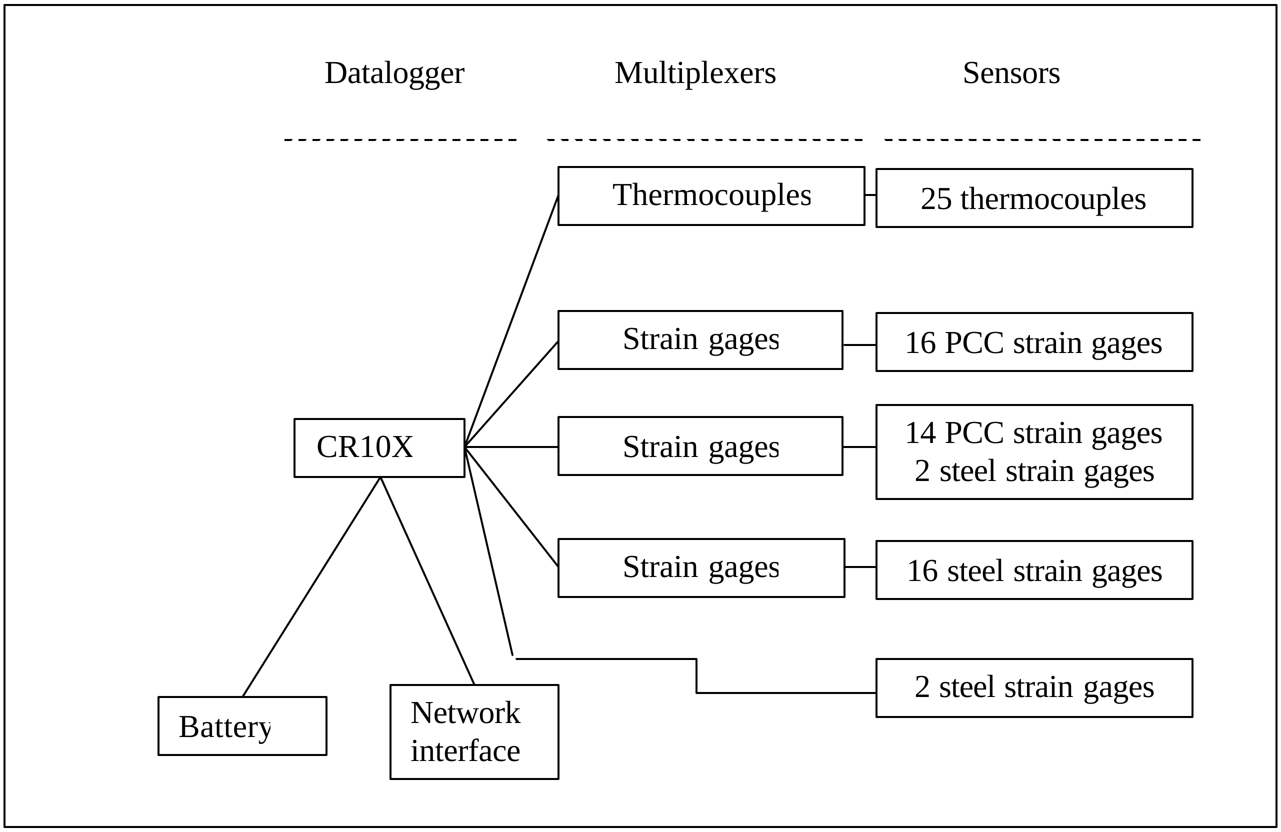


Figure 32. Components of Static Data Acquisition System.

The datalogging system for the dynamic sensors is a front-end signal conditioning system from National Instrument, known as SCXI (Signal Conditioning eXtensions for Instrumentation). This unit is connected to a personal computer located in the trailer from where the loading system is operated. SCXI is a modular platform for signal conditioning, and consists of multi-channel modules installed in a rugged chassis. This system is controlled with a program especially written with the software LabView, to collect and store data from the embedded dynamic concrete strain gages, from the LVDTs that measure deflection, and from thermocouples. The system also records the applied load and the (x,y) position of the load. The position is employed to synchronize the acquisition of data.

Sensor Installation General Procedure

Several steps were taken prior to installing the sensors on the test site. In selecting the critical location for each sensor, one of the criteria was the location of critical stress/strain. This was more important for the dynamic sensors than for the static system given that the load is applied at the edge of the CRC pavement and produces critical stresses at a single location depending on the crack spacing and concrete thickness. In contrast, the environmental effects measured by the static system are more uniformly applied to the CRC slabs. This resulted in locating the dynamic strain gages at positions of maximum stress due to a rolling wheel and placement of the static concrete and steel strain gages at locations of anticipated transverse cracks. In order to limit the damage to the static sensors during dynamic loading, the sensors were placed away from the loaded edge. The dynamic sensors were placed in the center 65 feet of each test section where the rolling wheel has a constant velocity.

ILLISLAB runs were made to predict the approximate location to place the dynamic strain gages. The maximum stress location for CRC slabs occurs at the top of the slab in the transverse direction and will generate a longitudinal crack (punchout distress) if this stress level is close to the concrete flexural strength. The following input parameters were explored in the ILLISLAB runs: the load was fixed at 40 kips; temperature differences top-bottom (0, -30 °F); 2 slab thicknesses (10 and 14 inches); crack spacing of 2, 4, or 6 feet; load transfer efficiency of 30 or 90 percent, and voids of different sizes under the slab were assumed. The finite element results indicated that the maximum stress occurred between 52 and 60 inches from the loaded edge for all cases analyzed. The dynamic strain gages were therefore placed 54.5 inches from the edge of CRC slabs.

Once the location of the strain gages were finalized, extension cables were added to the sensors in order to have them ready to be taken to the site and then attached to the dataloggers. The wires were soldered, and then isolated from one another and sealed using shrink-wrap tubing (Figure 33). Each sensor and cable was then labeled and the set of instruments for each section was grouped together.

Before attaching the steel strain gages, the surface of the rebars was prepared by removing the epoxy-coating and grinding the ribs off the rebar in the vicinity of the gage. The next step was to install supporting chairs for the concrete strain gages on the surface of the BAM base (Figure 34). The chairs are described in detail later along with the installation of the concrete sensors. The chairs were nailed to the BAM base prior to placement of the reinforcing steel.

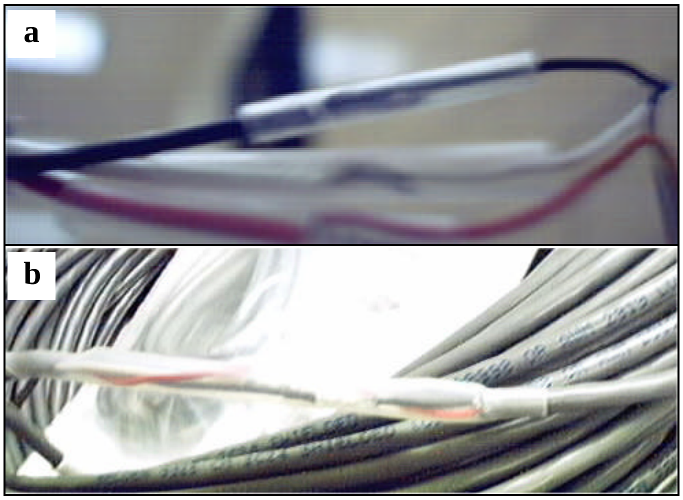


Figure 33. Pictures of tubings used to a) isolate and b) seal wire connections.

Figure 34. Chair used to support sensors.

Once all the embedded sensors were in place, the cables were then pulled to the center of each lane. The cables were passed under the paving form (Figure 36a) and into a 4-in. diameter PVC pipe. This PVC pipe was buried below the surface of the ground to prevent damage or cutting of the wires by the contractor's equipment. The sensor wires were brought to the pole where the datalogger was affixed. Cables from the dynamic concrete strain gages were not fed to the center of the lane, but to the center of each section, because they were to be attached later to the dynamic datalogging system. They were also passed under the paving form, but to the side that would be loaded, and kept safe in plastic electrical boxes inserted into the asphalt base (Figure 35b). Figures 36 A - B show pictures of one of the static dataloggers with all the cables hooked up to it.

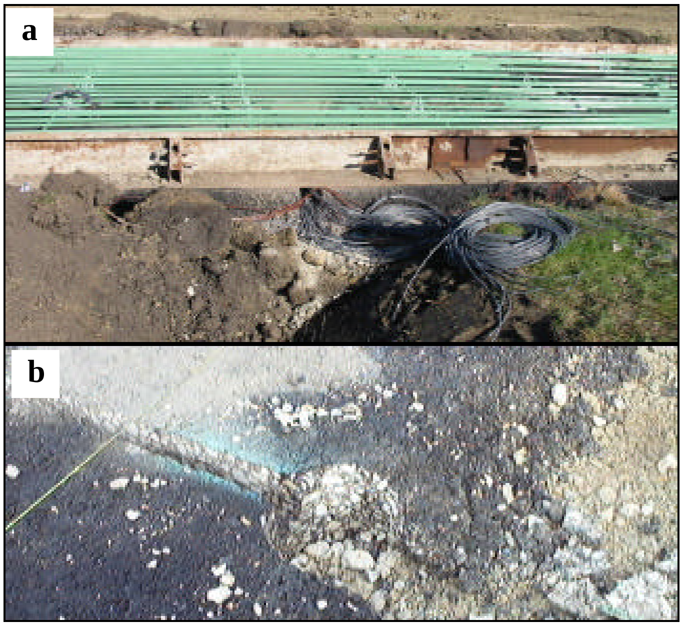
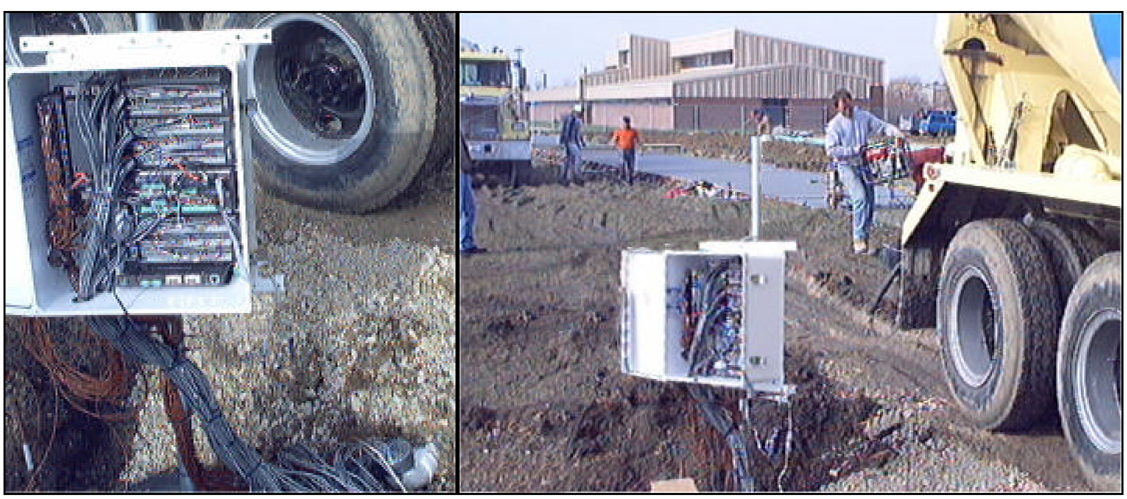


Figure 35. Pictures of one of the cuts to pass cables: a) central cut, b) cut in one section and the space for the box.



Figures 36 A - B. Datalogger operating during paving day.

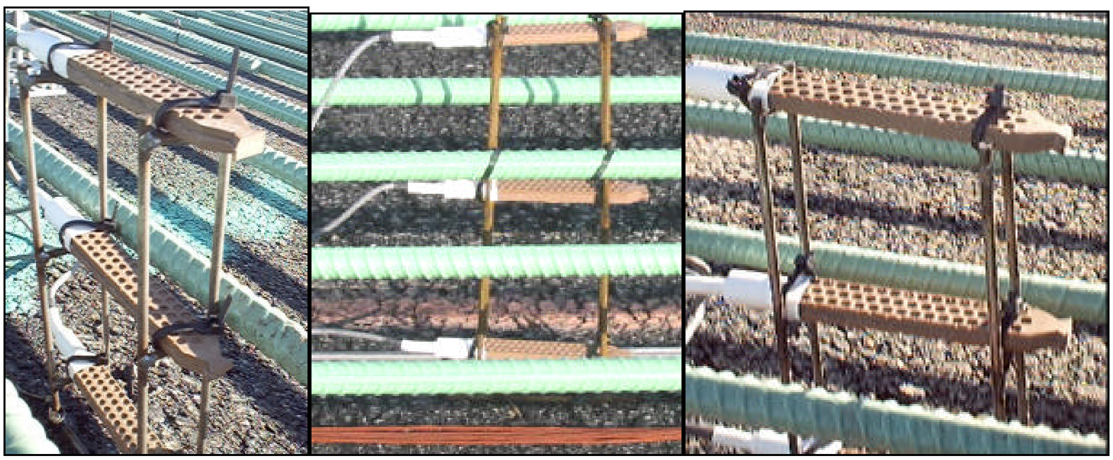
The last part in installing the sensors was to protect them during the paving process. This was accomplished using buckets to prevent the construction crew from stepping on the already placed instruments, as shown in Figures 37 A - B. Concrete was placed carefully around the buckets. When the paving screed approached the sensor, the bucket was removed and concrete was vibrated around the sensor.

Figures 37 A - B. Buckets to protect sensors during paving.

Sensors set up and location

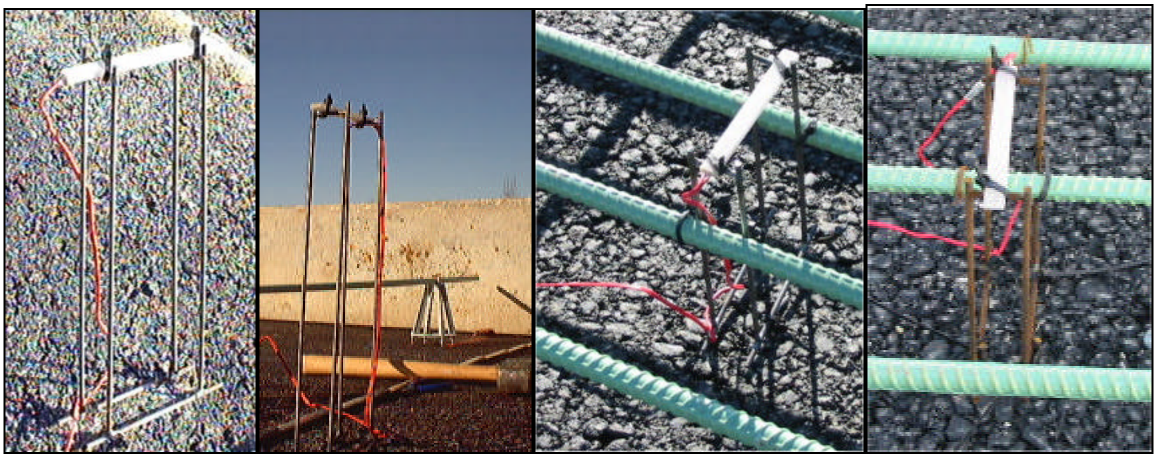
Each section of CRC pavement contains 6 static concrete strain gages, 4 steel strain gages, 5 thermocouple wires, and 4 dynamic concrete strain gages. These sensors were all embedded in the concrete during concrete paving. Vertical and horizontal LVDTs for the static system are being added as cracks become visible on the pavement surface. Vertical and horizontal LVDTs as well as several thermocouples were also attached as part of the dynamic data acquisition system. The following is a description of the specific details in installing each type of sensor and their locations.

Static concrete strain gages: These sensors were mounted and zip tied to thin steel chairs to hold them into the correct lateral and vertical position (Figures 38 A - C). Each side of the chair consists of a “ladder” which supports 3 strain gages. In the case of 10-inch pavements the chairs were designed to hold the sensors at 1, 5, and 9 inches from the surface of the BAM base. For the 14-inch pavement the sensors were put at 1, 7, and 13 inches from the surface of the BAM base. Two groups of 3 sensors were installed in each section, longitudinally oriented, and at approximately 7 feet from the loaded edge (the lanes are 12 feet wide).



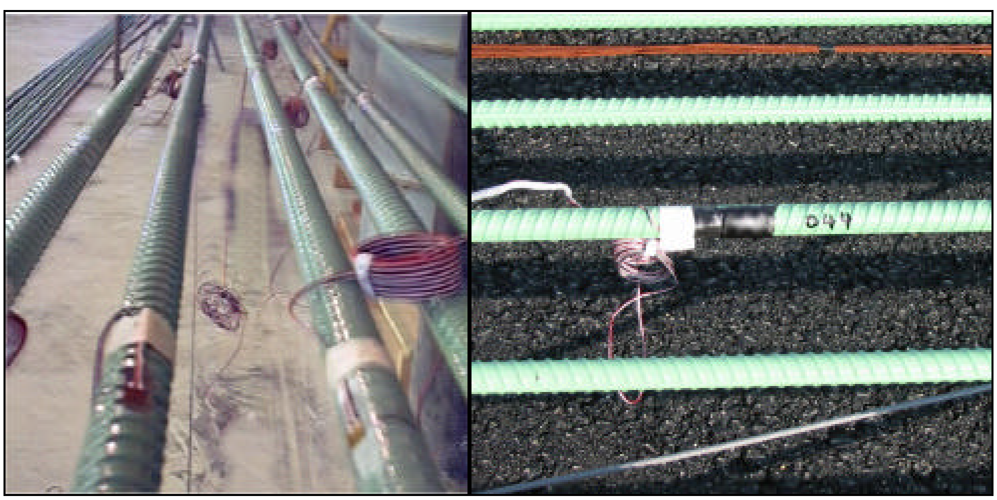
Figures 38 A - C. Pictures of concrete strain gages mounted on chairs.

Dynamic concrete strain gages: The dynamic strain gages were mounted to the same type of chairs as the static gages, as shown in Figures 39 A - D. The difference is that only one sensor was attached to each chair, either at 9 or 13 inches from the BAM base surface, depending on the pavement thickness (i.e., 1 inch from the CRCP surface). They were transversely oriented and at a distance from the loaded edge where the maximum stress is expected under a rolling wheel. This distance was determined to be approximately 54.5 inches using ILLISLAB.



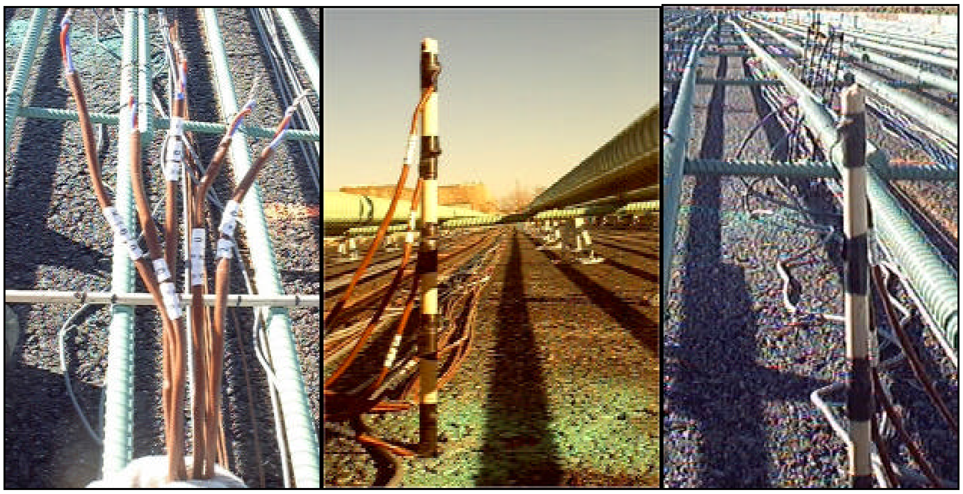
Figures 39 A - D. Pictures of dynamic concrete strain gages

Steel strain gages: The foil gages were bonded to reinforcement bars at 4 locations in the section. The gages were installed after removing the epoxy coating from the steel bars in areas of approximately 0.75 inch by 0.5 inch. After bonding the strain gage, a special coating layer was applied over the entire gage and terminal. A protective black insulation mastic followed to ensure waterproofing of the sensors. The steel strain gages are shown in Figures 40 A - B.



Figures 40 A - B. Pictures of steel strain gages before being sealed and then in-place.

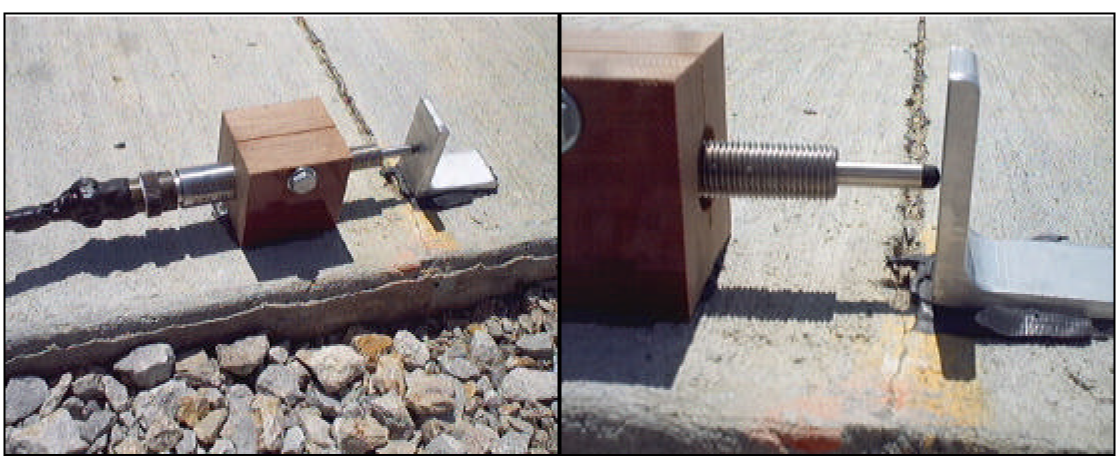
Thermocouples: Thermocouples for the static system wires were rolled out directly on the site and then attached to wooden dowels at approximately the center of each pavement section, as shown in Figures 41 A - C. The end of the thermocouples were manually twisted and then secured with electrical tape to the 3/8” wooden dowel. Five wires were installed in the concrete slab per section at 1, 3, 5, 7, and 9 inches from the surface of the BAM base. These vertical distances were 1, 4, 7, 10, and 13 inches for the 14- inch pavement. The dowels were inserted in holes drilled in the BAM and affixed with epoxy.



Figures 41 A - C. Pictures of thermocouple wires and wires mounted on wood dowels.

The thermocouples for the dynamic system are installed on wooden dowels too, but they are inserted into holes drilled in the pavement before the load begins to be applied on a specific section. Three dowels with 5 thermocouples each are inserted in different locations. The sensing wires are positioned at the top, center, and bottom of the pavement slab, and at 2 intermediate depths. The top sensor is approximately 0.04 inch under the surface.

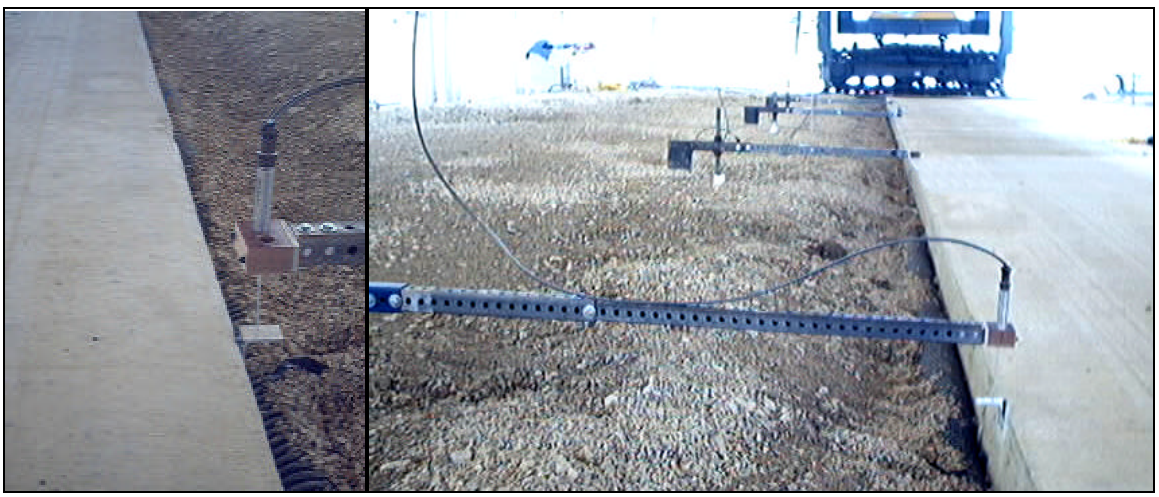
LVDTS: LVDTs were installed several months after construction. The horizontal sensors (Figures 42 A - B) were held in place using mounting blocks and the probe acts against an aluminum angle. Both parts were bonded to the pavement surface using heavy-duty epoxy. The sensors were located at representative cracks near the center of each section.



Figures 42 A - B. Horizontal LVDT for the static system.

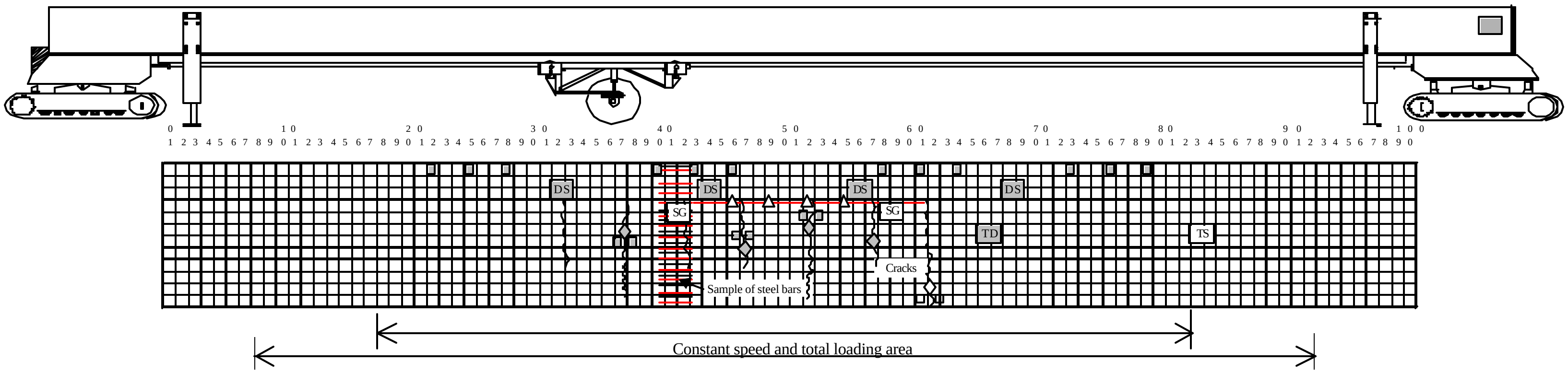
The vertical LVDTs for the static system were not installed at the time this report was written. They will be installed at the same cracks where the horizontal LVDTs are, and they will be mounted in a similar manner as the ones on the dynamic system (described next). There will be 1 horizontal and 2 vertical LVDTs per section.

The dynamic LVDTS are installed on a section just before loading with the ATLaS begins. There will be a total of 18 LVDTs to measure vertical deflection under load and 4 LVDTs to measure crack opening (horizontal). The vertical sensors will be mounted as shown in Figures 43 A - B with an aluminum angle attached to the side of the slab, in order to be able to load the pavement right at the edge. In the absence of cracks, only 4 or 5 of the vertical sensors could be installed, but when cracks become visible more sensors will be placed to measure deflection on both sides of the cracks. The horizontal dynamic LVDTs are installed the same way the static were mounted.



Figures 43 A - B. Vertical LVDTs for the dynamic system.

The location of sensors in a typical section is shown in Figure 44 along with the explanation of the symbols employed. The exact position of the embedded sensors in each section is presented in Appendix E. Figure 45 presents an overview of the location of the sensors.



	Symbol	Sensor	# per section
Static	SG	Static concrete strain gages [1]	6 (3 per chair)
	Δ	Steel strain gages	4
	□	Vertical deflection gages (static)	2
	◇	Horizontal deflection gages (static)	1
	TS	Thermocouple (static)	5 (all in 1 dowel)
Dynamic	DS	Dynamic concrete strain gages [1]	4
	■	Vertical deflection gages (dynamic)	18 [2]
	◆	Horizontal deflection gages (dynamic)	4 [2]
	TD	Thermocouple (dynamic)	15 [2]

Notes: [1] Static gages are oriented longitudinally and dynamic gages are oriented tranversely

[2] Only during loading period.

Figure 44. Instrumentation of a typical section and legend of symbols.

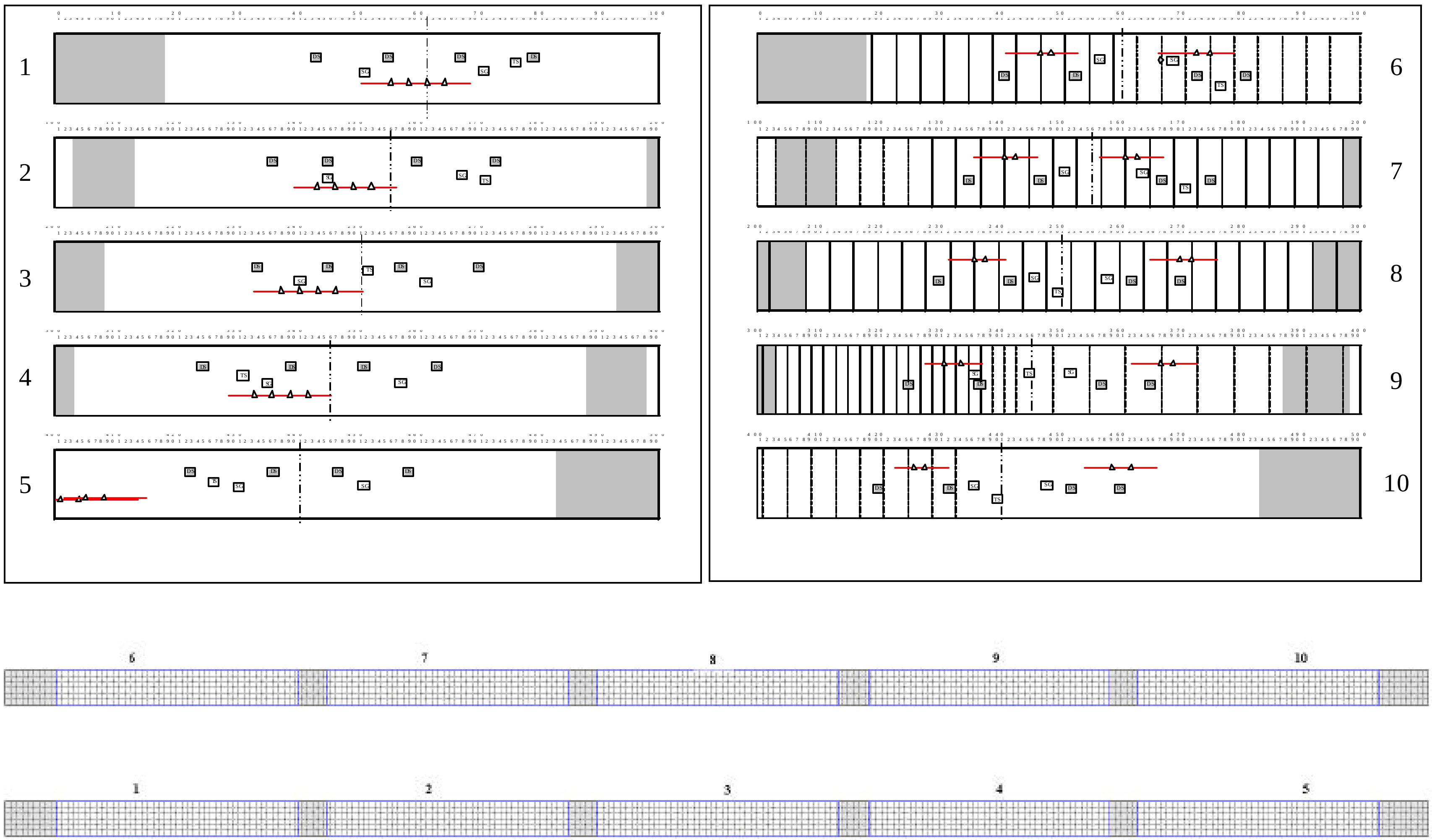


Figure 45. Location of embedded instruments in each section

Data collection and analysis

The program loaded into the static dataloggers establishes that at certain intervals the system activates and starts the process of collecting the signal for the whole set of sensors. Subsequently, the information is converted into the desired units, i.e. microstrains and degrees Celsius, and then stored in the internal memory. The accumulated data are later downloaded and processed in the office. The static system began operating a few hours before the concrete was poured on Lane 1. During the first 8 hours the system saved the data every minute, and for the next 48 hours the data were saved every 5 minutes. After this initial period, the system has been automatically collecting data every 30 minutes. The data files have been downloaded weekly. The dynamic system was about to begin operations by the time this report was written.

WEATHER STATION

In order to capture the climatological data to be included in the analysis, a weather station was installed at the site. The weather station records air temperature, humidity, wind speed, wind direction, and solar radiation. All the components are mounted on a single mast, including a datalogger as shown in Figures 46 A - C. Temperature and relative humidity are collected using the probe CS500 from Campbell Scientific Inc., housed inside a solar radiation shield. The probe contains a Platinum Resistance Temperature (PRT) detector and a capacitive relative humidity sensor. Incoming solar radiation is measured with LI200X Pyranometer, which contains a silicon photovoltaic detector. Wind speed and direction are measured with a propeller-type anemometer. The first image in Figure 46 shows, respectively, the wind monitor, the temperature and humidity probe, and the pyranometer.

Figures 46 A - C. Weather station.

VI. Concrete Pavement Materials

The steel and instrumentation placement was not completed until early December 2001. The contractor's plan for paving was to cast one lane per day. Due to the amount of instrumentation and short length of paving, the contractor chose to use side forms and a vibrating screed. The concrete mix design agreed upon by University, IDOT, and CIT was a Class PV mix with a maximum water to cement ratio of 0.42 and slump of 3 inches. The target flexural strength for this mix was approximately 550 psi at 14-days. Champaign Builder's Supply was the ready mix company supplying the fresh concrete. The theoretical mix design is detailed in Table 7 below.

Table 7. Concrete Mix Design

District 5 Mix Design No. 85PCC5658
Champaign Builders Supply Co. (P/S No. 357-01)

Cement (lbs./cy)	460
Fly Ash (lbs./cy)	145
Coarse Aggregate (lbs./cy)	1820
Fine Aggregate (lbs./cy)	1200
Water (lbs./cy)	242
Mortar Factor	0.85
Voids	0.42
Design w/c Ratio	0.40
Air Entraining Admixture (oz./cwt)	1.1 – 1.2
Water Reducer (oz./cwt)	3.5 – 4.0

The first day of PCC paving was on Monday, December 3, 2001. The air temperature was 45º F at 7:30 a.m. and increased throughout the day. The paving operation began at the west end of Lane 1 as shown in Figures 47 A - C. In addition to the vibrating screed, the contractor had one laborer running a stinger vibrator to consolidate the concrete around the steel. The fresh concrete properties tested by IDOT personnel are summarized in Table 8. The average slump of the concrete was higher than the maximum required under IDOT's specification for Class PV concrete. However, the haul time was approximately 30 minutes and hand placement warranted a little higher slump than originally anticipated. It appeared from the batch plant receipts that the maximum water to cement ratio was not being exceeded, which is one of the most important factors in achieving good performing concrete.

Table 8. Fresh Concrete Properties

	Sample	Total Yardage	Time	Air Content (%)	Slump (inches)	PCC Temp. (°F)
			Dec. 3, 2001			
Lane 1	1	8.5	7:40 a.m.	6.4	4 ¼	60
	2	58.5	9:15 a.m.	6.0	4 ½	60
	3	85.0	10:40 a.m.	6.9	4	63
	4	161.5	12:50 p.m.	7.0	3 ¼	66
			Dec. 5, 2001			
Lane 2	1	8.5	7:30 a.m.	5.8	4	65
	2	42.5	8:15 a.m.	5.3	3 ¾	67
	3	93.5	9:00 a.m.	6.7	4 ½	67
	4	136.0	10:30 a.m.	5.6	3	69
	5	170.0	11:30 a.m.	5.7	3 ¾	68

Figures 47 A - C. Paving Day 1

University of Illinois personnel made 4 beams and 4 cylinders at 2 separate locations in Lane 1. These beams and cylinders were used to determine the flexural strength and the elastic modulus of the concrete for future ATLaS testing. Three concrete prisms were also sampled for future determination of the concrete coefficient of thermal expansion.

The total paving time was approximately 8 hours for Lane 1. The tinning patterns on the surface on Lane 1 were as proposed (see Figure 48). However, the depth was about 1/16 inch rather than the proposed 1/32-inch depth. After the first lane's concrete was finished the contractor placed black plastic (HDPE) over the entire section. The curing sheets were placed at the west end of the section starting at 3:00 p.m. The pour was completed at 3:40 p.m. CIT used black plastic instead of blankets because the 72-hour forecast indicated no freezing temperatures.

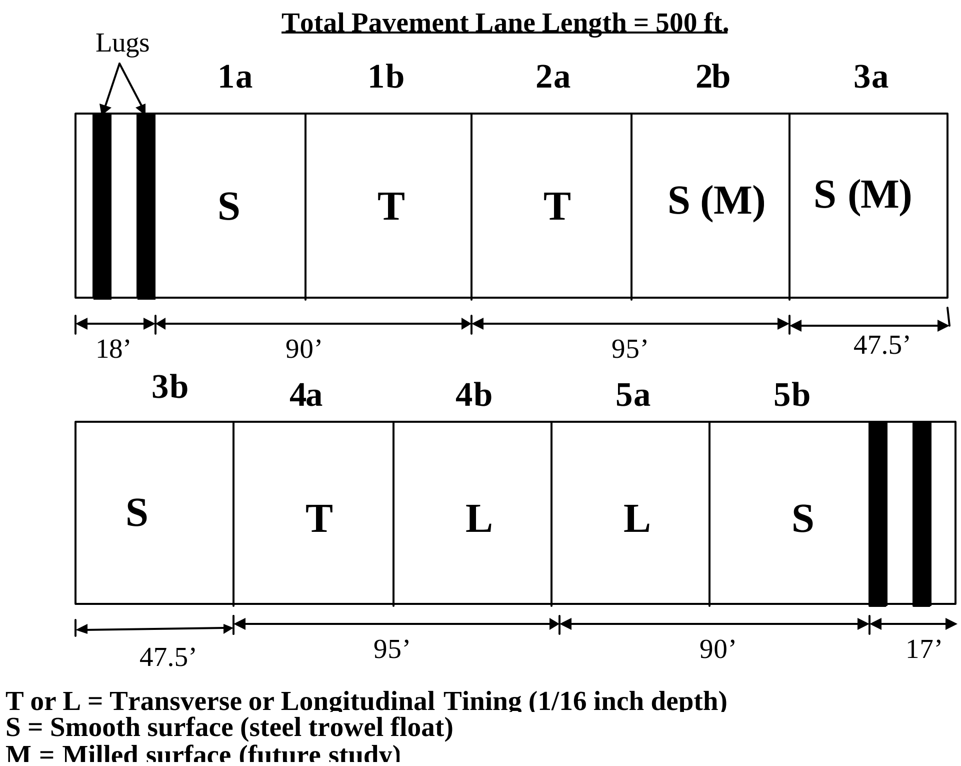


Figure 48. CRC Pavement Lane 1 Surface Preparation (Top view)

On the following day, some of the plastic sheeting had blown off Lane 1 due to wind. The contractor placed curing compound on the exposed pavement, then covered the pavement with plastic sheeting again. Also several of the 10-inch forms from Lane 1 were removed 24 hours after casting for use in Lane 2.

Lane 2 was paved on Wednesday, December 5, 2001 with similar temperature conditions that were encountered during Lane 1 paving. However, the wind speed was significantly higher during Lane 2 paving. The placement began at 7:30 a.m. and ended around 1:30 p.m. Lane 2 had similar fresh concrete properties as Lane 1, which are also shown in Table 8. Four beams and 4 cylinders at 2 separate locations were also made from the ready mix trucks for Lane 2.

One main goal of Lane 2 was the use of a tape inserter and Soff-Cut saw to induce cracking at regularly spaced intervals, ranging from 2 to 6 feet. The locations of the crack induced sections and saw-cutting were not the same as proposed due to the inserter running out of tape and then having to take apart the inserter to put new tape in it. The final locations of all the induced cracks can be found in Table 9. The crack inducing device began operating at 8:20 a.m., immediately after concrete placement. The automated crack-inducing device was used to create a weakened plane at the surface of the concrete. The depth of the induced crack was 3 inches. The cracks were induced following the paving screed as demonstrated in Figures 49 A - C. With one end of the tape c-clamped to the form, the crack inducing device was then pulled across the pavement, stretching the tape toward the opposite end. The tape was then cut so that about 6 inches of the pavement on each edge was left without the tape. In several places the concrete needed to be closed around the tape again. Overall the tape inserter was able to insert the tape without jamming or tearing the tape. The only problem with the tape inserter was that the weight of the device and depth of inserter fin disrupted the concrete surface because it would bump into the reinforcing steel at a 3.5-inch depth from the surface of the concrete. A finisher had to spend some time to re-work the concrete surface in the area of the tape (see Figures 50 A - B). The initial results of the prototype tape inserter indicated that proper weight balance and more vibration energy were required to enhance finishability, but the concept of inserting 3-mil tape as a weakened plane for cracking was proven successful.

Figures 49 A - C. Tape Inserter in Use

Figures 50 A - B. Reworking Concrete Surface After Tape Inserter Used

Table 9. Saw-cut and Crack Induction Schedule

Station (ft.)	Description	Interval
0-18	Lugs (none)	Lugs (none)
18-64	Saw-cut	4 ft.
64-130	Induced	4 ft.
130-302	Saw-cut	4 ft.
302-340	Saw-cut	2 ft.
340-345	Induced	2 ft.
345-397	Induced	6 ft.
397-433	Induced	4 ft.
433-483	Natural (none)	Natural (none)
483-500	Lugs (none)	Lugs (none)

The entire surface of Lane 2 was broomed approximately 2 hours after casting of the concrete materials. Concrete placement was completed at 12:45 p.m. The contractor began saw-cutting control cracks at 1:20 p.m. A Soff-Cut saw was used to cut a 1.5-inch notch on top of the CRCP surface. In some places, minor spalling occurred at the saw-cut due to the concrete not being mature enough. Curing blankets were used to cover the concrete in Lane 2, due to the forecasted freezing temperatures over the succeeding 72 hours. Thermal blankets for curing were placed at 1:45 p.m., immediately after sawing was completed. They consisted of heavy plastic with batting between them.

VII. <u>Early-age CRCP Properties</u>

Instrumentation data has been collected every 30 minutes for the first month after PCC paving. A graduate student is actively reviewing the data for inclusion in a report on the early-age behavior of the CRCP sections.

<u>CRACK PROGRESSION</u>

Crack surveys have been completed to monitor the cracking pattern development on Lanes 1 and 2. Lane 1 has shown no cracking within 100 feet of either end of the test lane as shown in Figure 51. However, the cracking on Lane 1 is very difficult to see due to the amount of surface tinning on the sections. Table 10 indicates the development of the cracks in Lane 1 over time. Overall, the Soff-Cut and tape used in Lane 2 have shown significant full-depth cracking at regular intervals relative to Lane 1. The Soff-Cut and tape notching appear to be creating cracks at the intended locations. After just over 1 month, all of the tape-inserted sections had formed cracks at their induced locations. The majority of the Soff-Cut sections had cracked during this same time frame, as shown in Table 11. There were a total of 37 Soff-Cut locations and 72 tape inserted locations, totaling 109 crack induced locations (Refer back to Table 9 for the crack induction schedule). There has been no cracking identified at non-induced locations along Lane 2 at this time.

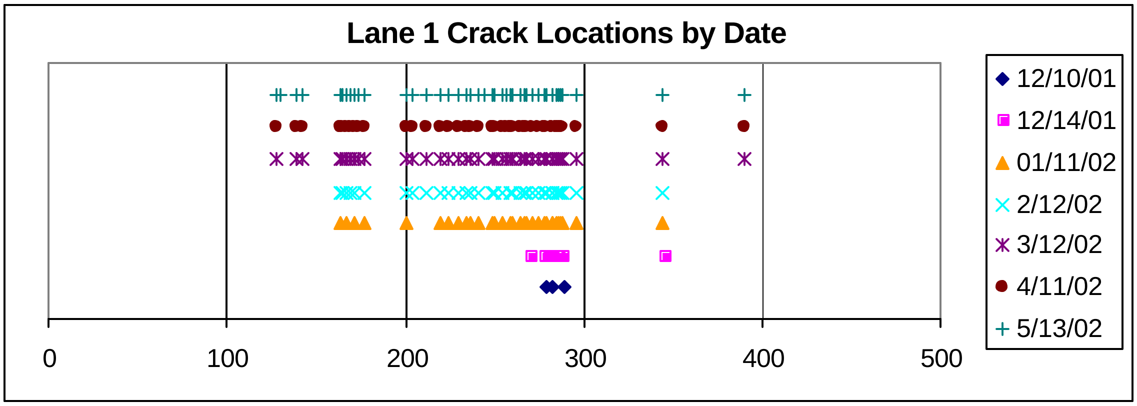


Figure 51. Natural crack progression over the length of the lane

Table 10. Crack Progression on Lane 1

Date	12/10/01	12/14/01	01/11/02	2/12/02	3/12/02	4/11/02	5/13/02
Days After Pour	7	11	39	71	99	129	161
Total Number of Cracks	3	10	31	35	41	41	43

Table 11. Crack Progression on Lane 2

Date	Total Induced	12/10/01	12/12/01	12/14/01	1/11/02	2/12/02	3/12/02	4/11/02	5/13/02
Days After Pour	0	5	7	9	37	69	97	127	159
Cracks formed at Tape Inserts	37	11	23	27	37	37	37	37	37
% of possible Tape cracks	-	30%	62%	73%	100%	100%	100%	100%	100%
Cracks formed at Soff-Cuts	72	17	42	43	58	58	59	59	61
% of possible Soff-Cut cracks	-	24%	58%	60%	81%	81%	82%	82%	85%
Natural cracks	0	0	0	0	0	0	0	0	3
All Cracks	109	28	65	70	95	95	96	96	99
% of ALL induced cracks	-	26%	60%	64%	87%	87%	88%	88%	88%

The progression of cracks for the two methods utilized is presented graphically in Figure 52.

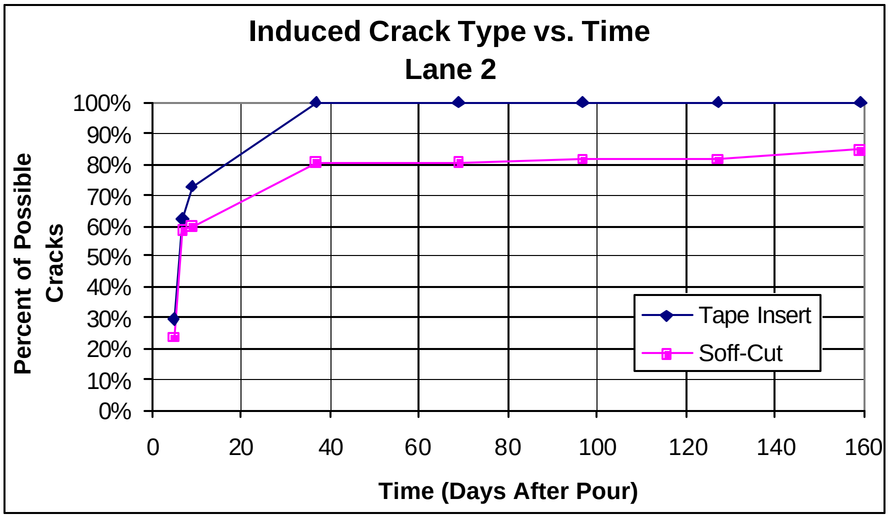


Figure 52. Percent of Cracks formed at Induced Locations (Lane 2)

<u>FWD TESTING</u>

Falling Weight Deflectometer testing was completed approximately 1 month after casting of the concrete. Wheel path testing at 50-foot centers was conducted on both lanes. From the FWD testing, the surface deflection of the PCC was measured. The results were normalized to 9,000- and 16,000-pound loads and can be seen in Figure 53. The average deflection was 2.6 mils at 9,000 pounds and approximately 4.6 mils at 16,000 pounds.

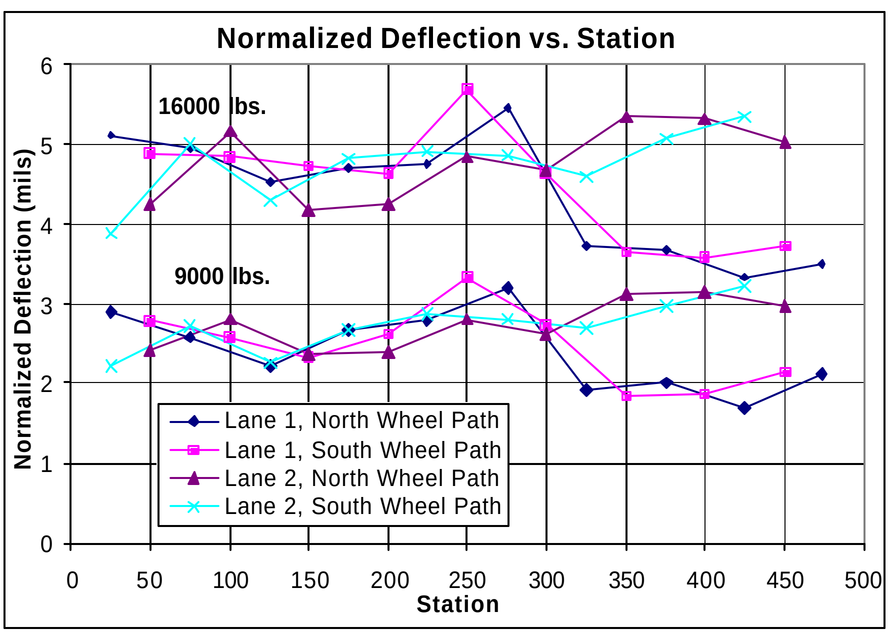


Figure 53. PCC FWD Normalized Deflections

The elastic modulus of the concrete was backcalculated according to the following procedure developed by Hall (1991). First, the AREA of the deflection was calculated using the same equation that was used to calculate this quantity for the BAM elastic modulus backcalculation.

Then the radius of relative stiffness (using the dense liquid foundation assumption) was determined for each tested location. From there, an effective k-value was backcalculated based on the center deflection equation from a distributed circular load with radius, *a*. Using this information, the PCC modulus was finally obtained.

Area, in inches = 6 * [D0 + 2D1 + 2D2 + D3] / D0

$$\ell_k = \left[\frac{\ln\left(\frac{36 - Area}{1812.279}\right)}{-2.55934} \right]^{4.387}$$

$$k = \left(\frac{P}{8k\ell_k^2}\right) * \left\{ 1 + \left(\frac{1}{2\pi}\right)\left[\ln\left(\frac{a}{2\ell_k}\right) + \gamma - 1.25\right]\left(\frac{a}{\ell_k}\right)^2 \right\}$$

$$\ell_k = \sqrt[4]{\frac{E_{pcc} h_{pcc}^3}{12(1 - \upsilon_{pcc}^2)k}} \text{ , therefore } E_{pcc} = \frac{12(1 - \upsilon^2)k\ell^4}{h^3}$$

where ℓ_k = dense liquid radius of relative stiffness (inches)
E_{pcc} = concrete elastic modulus (psi)
h_{pcc} = concrete thickness (inches)
υ = Poisson's ratio
k = modulus of subgrade reaction (psi/inch)
D0 = maximum deflection at center of load (inches)
P = load
a = loaded radius
γ = Euler's Constant = 0.57721566490

The effective k-value (of the subgrade and subbase) was determined to be 200 psi/inch. The average PCC modulus was backcalculated to be 8 x 10^6 psi. The variation of backcalculated k-value and PCC moduli along the length of the test sections are presented in Figure 54 and Figure 55. Detailed calculations are available in Appendix B.

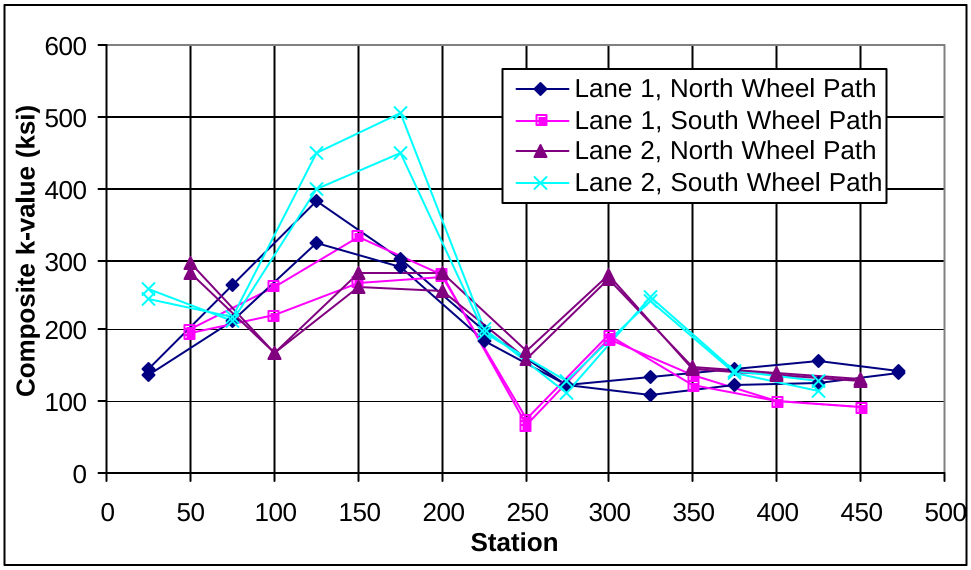


Figure 54. Effective k-value per Station

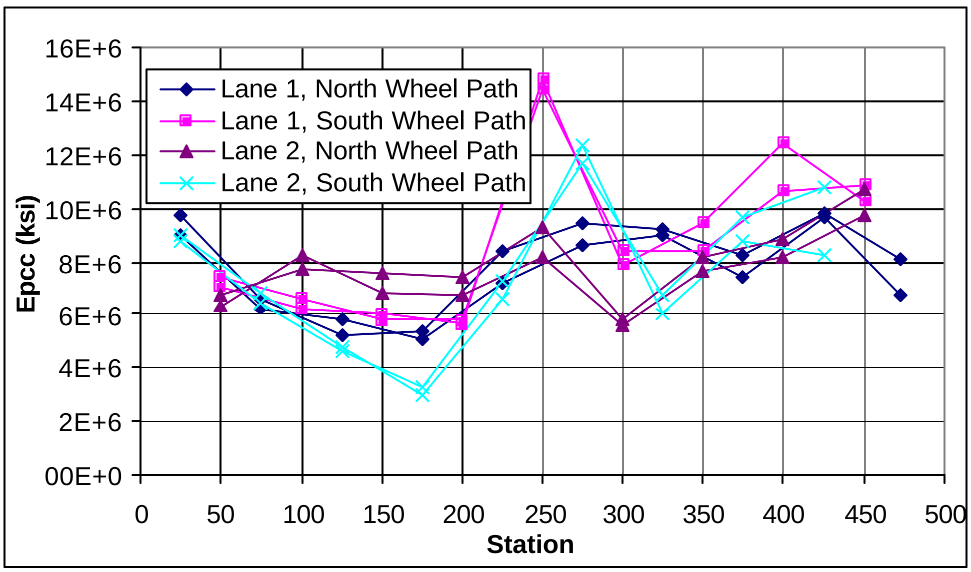


Figure 55. Epcc per Station

Load transfer efficiency (LTE) testing was done on several known cracks to begin to monitor the LTE changes with time. The average LTE for both Lane 1 and Lane 2 was determined to be 94 percent (see Figure 56 to Figure 58). A more detailed analysis can be examined in Appendix B.

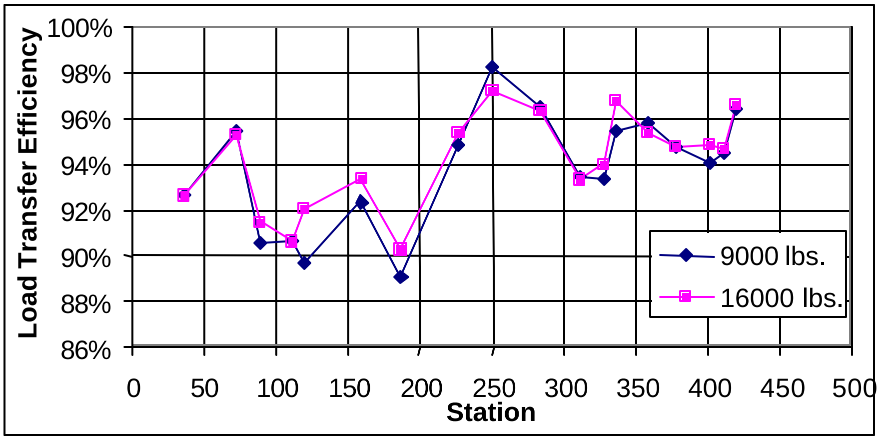


Figure 56. LTE by Weight, Lane 2 (Induced Cracks)

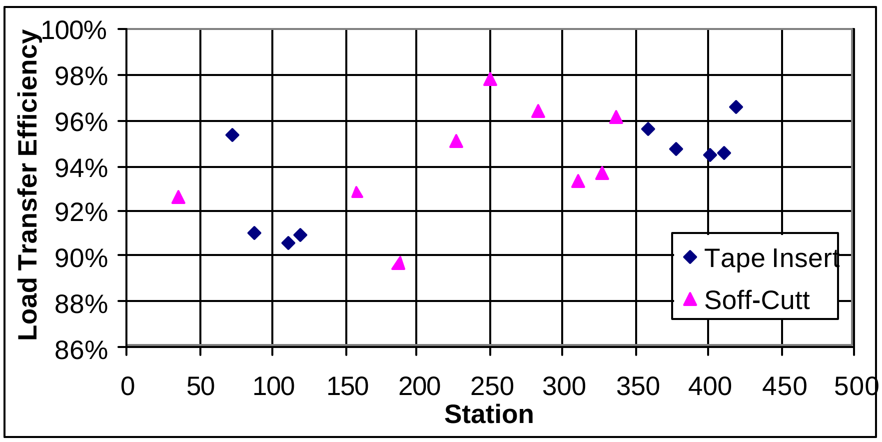


Figure 57. LTE by Crack Type, Lane 2 (Induced Cracks)

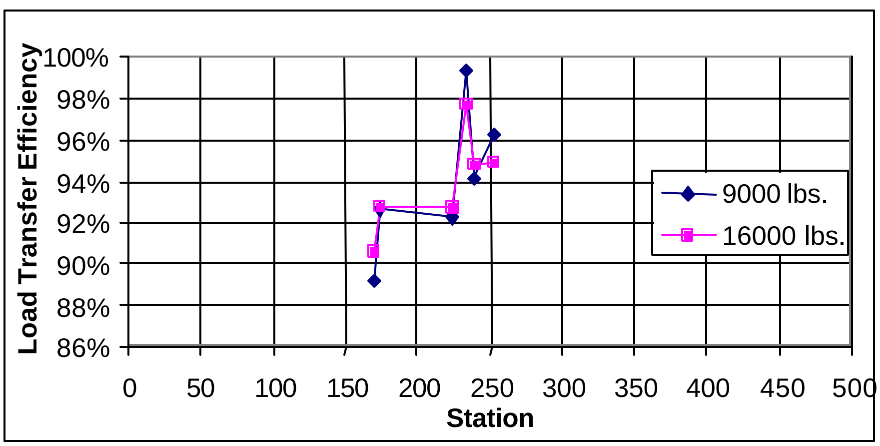


Figure 58. LTE by Weight, Lane 1 (Natural Cracking)

28-DAY CONCRETE STRENGTHS

The 28-day test results from the sampled beams and cylinders from both lanes are in Table 12 below.

Table 12. 28-Day Concrete Strength Results

	Modulus of Rupture, psi		E's and Compressive strength, ksi		
	Sample Location	MOR	Sample Location	E	? max
Lane 1	Section 2 beam1	641	Section 2 cyl 1	6764	5.78
Lane 1	Section 2 beam2	816	Section 2 cyl 2	7007	5.58
Lane 1	Section 4 beam1	795	Section 4 cyl 1	7248	5.65
Lane 1	Section 4 beam2	726	Section 4 cyl 2	7373	5.54
Lane 1	Average	745	Average	7098	5.64
Lane 1	Std. Dev.	79	Std. Dev.	270	0.11
Lane 2	east beam1	624	East cyl 1	6800	5.27
Lane 2	east beam2	697	East cyl 2	6272	6.17
Lane 2	west beam1	693	west cyl 1	6439	5.21
Lane 2	west beam2	712	west cyl 2	6960	5.58
Lane 2	Average	682	Average	6618	5.56
Lane 2	Std. Dev.	39	Std. Dev.	317	0.44
	Total Average	**713**	**Total Average**	**6858**	**5.60**
	Std. Dev.	**67**	**Std. Dev.**	**374**	**0.30**

VIII. All-Weather Shelter

The ATLaS was delivered to the ATREL site on December 17, 2001 by Applied Research Associates, Inc. In the beginning of January 2002, an all-weather shelter was constructed by University of Illinois personnel with the help of Sprung Systems (tent manufacturer). The purpose of the shelter is to protect the machine from the elements such as rain, snow, and direct sunlight. This shelter was completed during the last week of January 2002. The shelter is approximately 139 feet long, 50 feet wide, and 24 feet high. As shown in Figures 59 A - C, the Sprung shelter is made of flexible yet tough synthetic fabric panels on an aluminum skeleton frame.

The shelter is not heated or cooled, and therefore the environment will still have some impact on pavement responses. The shelter will need to be moved as the different CRCP sections are tested with the ATLaS. Currently, several approaches to move the shelter are being explored such as air pressuring and then towing, jacking and towing, and de-coupling the tent along its centerline and moving it with a crane.

Figures 59 A - C. Protective Tent

IX. References

Thompson, M.R. (1989), "ILLI-PAVE Based NDT Analysis Procedures," Nondestructive Testing of Pavements and Backcalculation of Moduli, ASTM STP 1026, A.J. Bush III and G.Y. Baladi, Eds., American Society for Testing and Materials, Philadelphia, pp. 487-501.

Hall, K.T. (1991), "Performance, Evaluation, and Rehabilitation of Asphalt-Overlaid Concrete Pavements," Ph.D. thesis, University of Illinois, Urbana, IL.

Appendix A

Soil Boring Logs

Soil Boring Log Key

Location: Lane #1 (southern lane)
ATREL, Rantoul, IL

Boring:	W-E Location of boring
1,1	50'
1,2	150'
1,3	250'
1,4	350'
1,5	450'

Location: Lane #2 (northern lane)
ATREL, Rantoul, IL

Boring:	W-E Location of boring
2,1	00'
2,2	100'
2,3	200'
2,4	300'
2,5	400'
2,6	500'

Blow Chart

Lane 1								
BORING #	**6"**	**12"**	**18"**	**24"**	**30"**	**36"**	**42"**	**48"**
1	8	8	8	6	7	5	6	6
2	9	11	10	11	11	14	12	12
3	8	6	6	7	7	9	7	7
4	7	4	5	4	4	7	8	7
5	6	5	5	6	6	7	8	11

Lane 2								
BORING #	**6"**	**12"**	**18"**	**24"**	**30"**	**36"**	**42"**	**48"**
1	11	10	11	9	12	11	10	10
2	8	6	6	7	10	11	9	10
3	5	5	8	8	10	10	10	13
4	4	6	5	3	4	6	4	7
5	4	4	4	4	6	8	8	7
6	4	5	5	6	6	7	8	9

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #1 (southern lane)
ATREL, Rantoul, IL

Boring: 1-1
Date of boring: July 26, 2001
Field representative: RMH

Depth	Visual Soil Classification Ground surface elevation: +1 ft	Sample No.	N	Qu (tsf)	MC (%)	Remarks
0"		--	--	--		* Lt brown from surface for entire depth * Took a bucket sample
6"			8			
	Lt/Dark Brown clayey Silt with root matter	1-1 12"			14	
12"			8			
18"			8			
	Orange/Brown fine sandy Clay with small gravel	1-1 24"*			11	
24"			6			
30"	Orange/Brown fine sandy Clay with small gravel	1-1 24"	7		10	
36"			5			
42"			6			
	Lt gray/Brown mottled silty Clay	1-1 48"			13	
48"			6			

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #1 (southern lane)
ATREL, Rantoul, IL

Boring: 1-2
Date of boring: July 26, 2001
Field representative: RMH

Visual Soil Classification Ground surface elevation: +1 ft	Depth	Sample No.	N	Qu (tsf)	MC (%)	Remarks
	0"	--	--	--		* Lt brown at surface
	6"		9			
Lt brown clayey Silt with sand and small gravel		1-2 12"		10		
	12"		11			
	18"		10			
Lt brown clayey Silt with sand and small gravel		1-2 24"*		11		
	24"		11			
Lt brown & gray mottled clayey Silt with sand and small gravel	30"	1-2 24"	11	12		* Took 3" diameter sample from 2' to 4' deep
	36"		14			
	42"		12			
Lt brown clayey Silt with sand and small gravel		1-2 48"		14		
	48"		12			

Soil Boring Log

Project:	CRCP - ATLaS	**Boring:**	1-3
Location:	Lane #1 (southern lane)	**Date of boring:**	July 26, 2001
	ATREL, Rantoul, IL	**Field representative:**	RMH

Visual Soil Classification Ground surface elevation: +1 ft	Depth	**Sample No.**	**N**	**Qu (tsf)**	**MC (%)**	**Remarks**
	0"	--	--	--		
	6"		8			
Lt brown clayey Silt with sand and small gravel		1-3 12"		15		
	12"		6			
	18"		6			
Dark brown clayey Silt with sand and small gravel		1-3 24"*		15		
	24"		7			* Dk to lt brown at approx. 24" deep
Brown, tan, grey mottled clayey Silt with small gravel	30"	1-3 24"	7	17		
	36"		9			
	42"		7			
Lt brown/gray, mottled clayey Silt with sand and small gravel		1-3 48"		17		
	48"		7			

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #1 (southern lane)
ATREL, Rantoul, IL

Boring: 1-4
Date of boring: July 26, 2001
Field representative: RMH

Visual Soil Classification Ground surface elevation: +1 ft	Depth	Sample No.	N	Qu (tsf)	MC (%)	Remarks
	0"	--	--	--		
	6"		7			
Dark brown clayey Silt with roots		1-4 12"			16	
	12"		4			
	18"		5			
Dark brown clayey Silt with small gravel		1-4 24"*			16	
	24"		4			
Gray/brown mottled clayey Silt with trace of sand and small gravel	30"	1-4 24"	4		17	
	36"		7			* Dk to lt brown at approx. 36" deep
	42"		8			
Gray/brown mottled clayey Silt with trace of sand and small gravel		1-4 48"			18	
	48"		7			

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #1 (southern lane)
ATREL, Rantoul, IL

Boring: 1-5
Date of boring: July 26, 2001
Field representative: RMH

Visual Soil Classification Ground surface elevation: +1 ft	Depth	Sample No.	N	Qu (tsf)	MC (%)	Remarks
	0"	--	--	--		
	6"		6			
Dark brown clayey Silt with roots		1-5 12"			14	
	12"		5			
	18"		5			
Dark brown clayey Silt with roots		1-5 24"*			20	
	24"		6			
Gray/brown mottled clayey Silt with sand and small gravel	30"	1-5 24"	6		22	
	36"		7			
	42"		8			
Brown/gray mottled clayey Silt with sand and small gravel		1-5 48"			23	
	48"		11			

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #2 (northern lane)
ATREL, Rantoul, IL

Boring: 2-1
Date of boring: July 26, 2001
Field representative: AVB

Visual Soil Classification Ground surface elevation: +1 ft	Depth	Sample No.	N	Qu (tsf)	MC (%)	Remarks
	0"	--	--	--		* Lt Brown from surface for entire depth
	6"		11			
Lt/Dark Brown clayey Silt with root matter		2-1 12"			9	
	12"		10			
	18"		11			
Lt/Dark Brown clayey Silt with small gravel		2-1 24"*			9	
	24"		9			
Lt/Dark Brown clayey Silt with small gravel	30"	2-1 24"	12		12	
	36"		11			
	42"		10			
Lt/Dark Brown clayey Silt with small gravel		2-2 48"			12	
	48"		10			

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #2 (northern lane)
ATREL, Rantoul, IL

Boring: 2-2
Date of boring: July 26, 2001
Field representative: AVB

Visual Soil Classification Ground surface elevation: +1 ft	Depth	Sample No.	N	Qu (tsf)	MC (%)	Remarks
	0"	--	--	--		* All Lt Brown from surface for entire depth.
	6"		8			
Lt/Dark Brown clayey Silt with small gravel and root matter		2-2 12"			12	
	12"		6			
	18"		6			
Brown clayey Silt with small gravel		2-2 24"*			11	
	24"		7			
Lt Brown clayey Silt with small gravel	30"	2-2 24"	10		13	
	36"		11			
	42"		9			
Lt Brown clayey Silt with small gravel		2-2 48"			13	
	48"		10			

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #2 (northern lane)
ATREL, Rantoul, IL

Boring: 2-3
Date of boring: July 26, 2001
Field representative: AVB

Depth	Visual Soil Classification Ground surface elevation: +1 ft	Sample No.	N	Qu (tsf)	MC (%)	Remarks
0"		--	--	--		* All Lt Brown from surface for the entire depth. * Took a bucket sample
6"			5			
	Lt/Dark Brown mottled Clayey silt with small gravel	2-3 12"			10	
12"			5			
18"			8			
	Lt Brown clayey Silt with small gravel	2-3 24"*			8	
24"			8			
30"	Lt Brown clayey Silt with small gravel	2-3 24"	10		12	
36"			10			
42"			10			
	Lt Brown clayey Silt with small gravel	2-3 48"			13	
48"			13			

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #2 (northern lane)
ATREL, Rantoul, IL

Boring: 2-4
Date of boring: July 26, 2001
Field representative: AVB

Depth	Visual Soil Classification Ground surface elevation: +1 ft	Sample No.	N	Qu (tsf)	MC (%)	Remarks
0"		--	--	--		* Dark brown down to 12"
6"			4			
	Dark Brown / Brown Clayey silt with small gravel and root matter	2-4 12"			13	
12"			6			* Change to light brown @ 12"
18"			5			
	Lt Brown clayey Silt with small gravel	2-4 24"*			9	
24"			3			
30"	Lt Brown clayey Silt with small gravel	2-4 24"	4		15	
36"			6			
42"			4			
	Lt Brown clayey Silt with small gravel	2-4 48"			13	
48"			7			

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #2 (northern lane)
ATREL, Rantoul, IL

Boring: 2-5
Date of boring: July 26, 2001
Field representative: AVB

Visual Soil Classification Ground surface elevation: +1 ft		Sample No.	N	Qu (tsf)	MC (%)	Remarks
	0"	--	--	--		
	6"		4			
Dark Brown / Brown Clayey silt with small gravel and root matter		2-5 12"			14	
	12"		4			
	18"		4			
Brown Clayey silt with small gravel		2-5 24"*			18	
	24"		4			* at approx 24" color changes from dark Brown to Gray
Brown / Gray mottled Clayey silt	**30"**	2-5 24"	6		18	* Took a 3" core sample btwn 2' - 4' deep
	36"		8			
	42"		8			
Dark Brown / Brown mottled clayey Silt with small gravel		2-5 48"			21	
	48"		7			* at 48" color goes to orange

Soil Boring Log

Project: CRCP - ATLaS
Location: Lane #2 (northern lane)
ATREL, Rantoul, IL

Boring: 2-6
Date of boring: July 26, 2001
Field representative: AVB

Visual Soil Classification Ground surface elevation: +1 ft	Depth	Sample No.	N	Qu (tsf)	MC (%)	Remarks
	0"	--	--	--		
	6"		4			
Dark Brown / Brown Clayey silt with small gravel and root matter		2-6 12"			17	
	12"		5			
	18"		5			
Dark Brown / Brown / Gray Clayey silt with small gravel		2-6 24"*			19	
	24"		6			* Change to Lt Brown at 24"
Lt Brown / Gray mottled clayey Silt w/ sand and small gravel	30"	2-6 24"	6		21	
	36"		7			
	42"		8			
Dark Brown / Gray mottled clay Silt w/ sand and small gravel		2-6 48"			25	* Change to Orange / Gray at 48"
	48"		9			

Appendix B

FWD AC, PCC, and LTE Results

FWD Backcalculations For BAM Layer

BAM Thickness (T_{BAM}) = 4 in.

Diameter of Plate = 11.8 in.
Target Load = 9000 lbs.

At start of test:
Air Temperature (F) = 73
Pvmt Temp @ 2 inch = 60
At end of test:
Air Temperature (F) = 72
Pvmt Temp @ 2 inch = 75

Algorithms developed by Elliot et al., 1985
(For 9000 lb impulse type loading with a 12" diameter loading plate.)
$\text{Log}(E_{AC}) = 1.48 + 1.76 * \text{Log}(\text{Area}/D0) + 0.26 * (\text{Area}/T_{AC})$
$\text{Log}(E_{Ri}) = 1.51 - 0.19 * D3 + 0.27 * \text{Log}(D3)$
Area = 6 * (D0 + 2D1 + 2D2 + D3)/D0

EB Lane 1 (South Wheel Path)
Pavement Temp. = 75

STA	Measured					Normalized			BAM Mod.	Subgrade
	Weight	D0 = 0"	D1 = 12"	D2 = 24"	D3 = 36"	Weight	D0 = 0"	Area	E_{BAM}	E_{Ri}
	lbs.	mils	mils	mils	mils	lbs.	mils	in.	ksi	ksi
50	8779	45.82	34.30	19.86	9.97	9000	46.97	21.49	199	0.77
100	8684	48.59	37.31	21.35	9.82	9000	50.36	21.70	188	0.82
150	8680	44.84	32.69	17.06	7.30	9000	46.49	20.29	156	2.27
200	8775	41.92	30.82	16.04	6.78	9000	42.99	20.38	179	2.79
250	8819	36.13	27.39	16.30	8.83	9000	36.87	21.98	338	1.22
300	8974	30.68	22.69	13.33	7.35	9000	30.77	21.53	406	2.23
350	8891	33.16	24.91	14.67	7.97	9000	33.57	21.77	374	1.73
400	8942	32.38	24.51	14.32	8.01	9000	32.59	21.87	400	1.71
450	8724	35.19	27.57	16.77	9.10	9000	36.30	22.67	415	1.10
						Average	39.66		295	1.63
						Variance	51.37		12389	0.50
						Std. Dev.	7.17		111	0.71

WB Lane 2 (North Wheel Path)
Pavement Temp. = 81

STA	Measured					Normalized			BAM Mod.	Subgrade
	Weight	D0 = 0"	D1 = 12"	D2 = 24"	D3 = 36"	Weight	D0 = 0"	Area	E_{BAM}	E_{Ri}
	lbs.	mils	mils	mils	mils	lbs.	mils	in.	ksi	ksi
50	8736	38.11	27.33	13.25	4.95	9000	39.26	19.56	174	5.72
100	8732	41.35	27.93	13.60	6.25	9000	42.62	18.96	131	3.45
150	8672	45.82	35.07	19.73	8.61	9000	47.55	21.48	198	1.34
200	8620	47.02	36.24	20.36	8.83	9000	49.09	21.57	193	1.22
250	8799	34.25	24.14	12.93	6.61	9000	35.03	20.15	242	2.99
300	8744	38.82	29.28	16.59	7.95	9000	39.96	21.41	261	1.75
350	8664	49.35	35.06	17.95	8.11	9000	51.26	19.88	119	1.64
400	8787	42.52	31.17	17.21	8.40	9000	43.55	20.84	195	1.46
450	8676	42.59	31.83	17.66	8.88	9000	44.18	21.20	211	1.20
						Average	43.61		192	2.31
						Variance	26.42		2127	2.28
						Std. Dev.	5.14		46	1.51

EB Lane 1 (North Wheel Path)

Pavement Temp. = 81

STA	Measured Weight	Measured D0 = 0"	Measured D1 = 12"	Measured D2 = 24"	Measured D3 = 36"	Normalized Weight	Normalized D0 = 0"	Area	BAM Mod. E_{BAM}	Subgrade E_{Ri}
	lbs.	mils	mils	mils	mils	lbs.	mils	in.	ksi	ksi
25	8501	57.30	43.73	24.14	11.00	9000	60.66	21.37	130	0.50
75	8700	47.00	37.59	23.09	12.14	9000	48.62	23.04	271	0.31
125	8438	51.00	37.99	20.33	8.37	9000	54.40	20.71	137	1.48
175	8700	36.41	27.11	14.31	6.00	9000	37.67	20.64	244	3.80
225	8732	35.04	25.44	13.54	6.17	9000	36.12	20.41	247	3.56
275	8819	35.37	26.04	14.71	7.80	9000	36.10	21.15	289	1.86
325	8732	35.91	26.52	15.17	8.12	9000	37.01	21.29	291	1.63
375	9184	33.97	25.94	15.33	8.67	9000	33.29	22.11	388	1.31
425	8664	36.29	27.15	15.54	8.30	9000	37.70	21.49	299	1.52
475	8879	31.39	23.64	13.82	7.65	9000	31.82	21.78	414	1.97
						Average	41.34		271	1.79
						Variance	94.74		8292	1.28
						Std. Dev.	9.73		91	1.13

WB Lane 2 (South Wheel Path)

Pavement Temp. = 81

STA	Measured Weight	Measured D0 = 0"	Measured D1 = 12"	Measured D2 = 24"	Measured D3 = 36"	Normalized Weight	Normalized D0 = 0"	Area	BAM Mod. E_{BAM}	Subgrade E_{Ri}
	lbs.	mils	mils	mils	mils	lbs.	mils	in.	ksi	ksi
25	8787	29.26	20.26	9.72	4.00	9000	29.97	19.12	250	8.18
75	8469	54.78	42.31	23.09	9.34	9000	58.21	21.35	140	0.99
125	8628	42.33	33.42	19.27	8.85	9000	44.16	22.19	268	1.21
175	8628	44.64	33.53	18.30	7.57	9000	46.56	20.95	183	2.04
225	8732	37.85	26.64	13.62	6.22	9000	39.01	19.75	185	3.49
275	8759	30.75	23.86	14.71	8.50	9000	31.60	22.71	530	1.40
325	8696	34.86	26.17	14.84	7.50	9000	36.08	21.41	315	2.10
375	8656	46.14	33.46	18.06	8.78	9000	47.97	20.54	157	1.25
425	8692	45.42	33.20	18.05	9.19	9000	47.03	20.75	170	1.06
475	8628	40.31	29.49	16.58	8.16	9000	42.05	20.93	218	1.61
						Average	42.26		242	2.33
						Variance	71.74		13244	4.76
						Std. Dev.	8.47		115	2.18
					Total	Average	41.72		250	2.02
					Total	Variance	59.34		9835	2.17
					Total	Std. Dev.	7.70		99	1.47

FWD Backcalculations For PCC Pavement

1/10/2002

Diameter of Plate =	11.8	in.
Target Load =	9000	lbs.
	16000	lbs.

At start of test:		At end of test:	
Air Temperature (F)=	38 Cloudy	Air Temperature (F) =	42
Pvmt Temp (F) =	35	Pvmt Temp (F) =	39

PCC height = 11" (except on Lane 1 from STA 298 to 483 where PCC height = 15")
This assumes an extra inch of pavement was actually constructed

a = Radius of loaded area = 5.9 in.
γ = Euler's constant = 0.5772157
υ = Poisson's ratio = 0.15

Algorithms based on Westergaard's interior loading (Hall-1991)
Area = 6 * (D0 + 2D1 + 2D2 + D3)/D0
$l_k = \{\ln[(36 - \text{Area})/1812.279] / (-2.55934)\}^{4.387}$
$k = [P/(8 * D0 * l_k^2) * \{1 + (1/2\pi) * [\ln(a/2l_k) + \gamma - 1.25] * (a/l_k)^2\}$
$E_{pcc} = 12 * k * l^4 * (1-\upsilon^2)/h^3$

WB Lane 2 (North Wheel Path)
Pavement Temp. = 35

STA	Measured Weight	Measured D0 = 0"	Measured D1 = 12"	Measured D2 = 24"	Measured D3 = 36"	Normalized Weight	Normalized D0 = 0"	Area	PCC Thickness	Radius of Rel. Stiff.	Composite k-value	Epcc
	lbs.	mils	mils	mils	mils	lbs.	mils	in.	in.	in.	$lb/in.^2/in.$	$lb/in.^2$
50	8664	2.32	2.15	1.90	1.61	9000	2.41	31.11	11	39.5	296	6.3E+6
	15588	4.14	3.86	3.41	2.92	16000	4.25	31.30	11	40.7	282	6.8E+6
100	8930	2.78	2.66	2.42	2.04	9000	2.80	32.33	11	48.6	169	8.3E+6
	15692	5.06	4.82	4.40	3.69	16000	5.16	32.24	11	47.8	169	7.7E+6
150	8616	2.28	2.12	1.91	1.56	9000	2.38	31.32	11	40.7	282	6.8E+6
	15628	4.07	3.81	3.45	2.83	16000	4.17	31.58	11	42.5	263	7.6E+6
200	8847	2.35	2.17	1.96	1.65	9000	2.39	31.30	11	40.6	282	6.8E+6
	15723	4.18	3.89	3.54	2.97	16000	4.25	31.59	11	42.6	256	7.4E+6
250	8787	2.74	2.59	2.39	2.05	9000	2.81	32.30	11	48.3	170	8.2E+6
	15628	4.73	4.50	4.17	3.59	16000	4.84	32.55	11	50.7	159	9.3E+6
300	9026	2.64	2.44	2.15	1.82	9000	2.63	31.00	11	38.8	280	5.6E+6
	15842	4.63	4.30	3.78	3.21	16000	4.68	31.10	11	39.4	272	5.8E+6
350	8787	3.06	2.89	2.67	2.35	9000	3.13	32.41	11	49.4	146	7.6E+6
	15763	5.27	5.00	4.60	4.06	16000	5.35	32.48	11	50.0	148	8.2E+6
400	8708	3.04	2.93	2.66	2.29	9000	3.14	32.59	11	51.1	136	8.2E+6
	15660	5.21	5.03	4.57	3.95	16000	5.32	32.66	11	51.9	138	8.9E+6
450	8819	2.91	2.80	2.57	2.29	9000	2.97	32.87	11	54.2	128	9.8E+6
	15779	4.94	4.74	4.39	3.93	16000	5.01	32.95	11	55.3	130	10.7E+6
					average deflection at 9000 lbs		2.74		Average	46.2	206	7.8E+6
					average deflection at 16000 lbs.		4.78		Variance	30.9	4442	1.8E+12
									Std. Dev.	5.6	67	1.3E+6

EB Lane 1 (South Wheel Path)
Pavement Temp. = 35

STA	Measured Weight	Measured D0 = 0"	Measured D1 = 12"	Measured D2 = 24"	Measured D3 = 36"	Normalized Weight	Normalized D0 = 0"	Area	PCC Thickness	Radius of Rel. Stiff.	composite k-value	Epcc
	lbs.	mils	mils	mils	mils	lbs.	mils	in.	in.	in.	$lb/in.^2/in.$	$lb/in.^2$
50	8740	2.70	2.54	2.29	1.99	9000	2.78	31.89	11	44.8	200	7.1E+6
	15501	4.73	4.45	4.04	3.51	16000	4.88	31.99	11	45.6	195	7.4E+6
100	9451	2.70	2.50	2.26	1.86	9000	2.57	31.29	11	40.6	263	6.3E+6
	15846	4.80	4.48	4.11	3.34	16000	4.85	31.65	11	43.0	221	6.7E+6
150	10341	2.67	2.43	2.17	1.85	9000	2.32	30.83	11	37.9	333	6.0E+6
	16132	4.76	4.40	3.90	3.34	16000	4.72	31.13	11	39.6	267	5.8E+6
200	8569	2.50	2.30	2.04	1.75	9000	2.63	31.03	11	39.0	278	5.7E+6
	15505	4.49	4.13	3.67	3.18	16000	4.63	31.10	11	39.4	275	5.8E+6
250	8521	3.16	3.17	2.89	2.57	9000	3.34	33.89	11	70.7	67	14.8E+6
	15465	5.49	5.47	5.01	4.46	16000	5.68	33.78	11	68.4	75	14.5E+6
300	8612	2.61	2.44	2.24	2.01	9000	2.73	32.14	11	46.8	186	7.9E+6
	15497	4.49	4.20	3.85	3.49	16000	4.64	32.18	11	47.2	192	8.4E+6
350	10352	2.12	2.07	1.94	1.77	9000	1.84	33.71	15	67.0	136	9.5E+6
	16017	3.65	3.56	3.34	3.04	16000	3.65	33.68	15	66.5	124	8.4E+6
400	10245	2.12	2.09	1.97	1.83	9000	1.86	34.16	15	77.2	101	12.5E+6
	16172	3.63	3.55	3.38	3.11	16000	3.59	34.05	15	74.4	100	10.7E+6
450	8815	2.11	2.07	1.96	1.82	9000	2.15	34.09	15	75.5	91	10.3E+6
	15862	3.69	3.62	3.44	3.18	16000	3.72	34.13	15	76.4	92	10.9E+6
					average deflection at 9000 lbs		2.47		Average	55.5	178	8.8E+6
					average deflection at 16000 lbs.		4.48		Variance	243.7	6842	8.5E+12
									Std. Dev.	15.6	83	2.9E+6

WB Lane 2 (South Wheel Path)

Pavement Temp. = 36

STA	Measured Weight	Measured D0 = 0"	Measured D1 = 12"	Measured D2 = 24"	Measured D3 = 36"	Normalized Weight	Normalized D0 = 0"	Area	PCC Thickness	Radius of Curvature	composite k-value	Epcc
	lbs.	mils	mils	mils	mils	lbs.	mils	in.	in.	in.	lb/in.^{2}/in.	lb/in.^{2}
25	8458	2.09	1.98	1.77	1.53	9000	2.22	31.92	11	45.1	247	9.0E+6
	15449	3.75	3.53	3.17	2.74	16000	3.88	31.82	11	44.3	260	8.8E+6
75	9041	2.72	2.56	2.29	1.95	9000	2.71	31.70	11	43.4	219	6.8E+6
	15695	4.91	4.58	4.15	3.55	16000	5.01	31.67	11	43.2	212	6.5E+6
125	9435	2.36	2.11	1.81	1.53	9000	2.25	29.82	11	33.1	450	4.7E+6
	15795	4.24	3.81	3.29	2.77	16000	4.30	30.01	11	33.9	400	4.6E+6
175	8891	2.63	2.24	1.92	1.58	9000	2.66	28.59	11	28.7	505	3.0E+6
	15632	4.70	4.06	3.51	2.92	16000	4.81	29.06	11	30.2	448	3.3E+6
225	8505	2.71	2.52	2.30	2.00	9000	2.87	31.77	11	43.9	202	6.6E+6
	15473	4.75	4.44	4.07	3.53	16000	4.91	31.96	11	45.3	196	7.3E+6
275	8541	2.67	2.57	2.40	2.19	9000	2.81	33.26	11	59.4	113	12.4E+6
	15409	4.67	4.46	4.17	3.81	16000	4.85	33.07	11	56.8	127	11.7E+6
325	8573	2.57	2.38	2.13	1.82	9000	2.70	31.31	11	40.7	249	6.0E+6
	15541	4.45	4.15	3.72	3.20	16000	4.58	31.54	11	42.2	243	6.8E+6
375	8712	2.88	2.73	2.52	2.28	9000	2.98	32.63	11	51.5	141	8.8E+6
	15624	4.94	4.71	4.35	3.90	16000	5.06	32.74	11	52.8	141	9.7E+6
425	8620	3.09	2.96	2.72	2.38	9000	3.23	32.68	11	52.1	127	8.3E+6
	15664	5.22	5.07	4.67	4.10	16000	5.33	33.10	11	57.3	114	10.8E+6
						average deflection at 9000 lbs	2.71		Average	44.7	244	7.5E+6
						average deflection at 16000 lbs.	4.75		Variance	84.6	15589	7.1E+12
									Std. Dev.	9.2	125	2.7E+6

EB Lane 1 (North Wheel Path)

Pavement Temp. = 36

STA	Measured Weight	Measured D0 = 0"	Measured D1 = 12"	Measured D2 = 24"	Measured D3 = 36"	Normalized Weight	Normalized D0 = 0"	Area	PCC Thickness	Radius of Curvature	composite k-value	Epcc
	lbs.	mils	mils	mils	mils	lbs.	mils	in.	in.	in.	lb/in.^{2}/in.	lb/in.^{2}
25	8605	2.77	2.65	2.43	2.13	9000	2.90	32.62	11	51.5	145	9.0E+6
	15497	4.94	4.75	4.35	3.85	16000	5.10	32.78	11	53.3	137	9.7E+6
75	9939	2.84	2.61	2.35	2.04	9000	2.57	31.27	11	40.4	265	6.2E+6
	15866	4.91	4.59	4.13	3.59	16000	4.95	31.70	11	43.4	213	6.6E+6
125	10480	2.57	2.32	2.04	1.78	9000	2.21	30.51	11	36.2	384	5.8E+6
	16275	4.59	4.16	3.69	3.14	16000	4.51	30.63	11	36.8	323	5.2E+6
175	8537	2.53	2.36	2.02	1.65	9000	2.67	30.69	11	37.1	303	5.0E+6
	15437	4.54	4.26	3.65	2.99	16000	4.71	30.86	11	38.0	290	5.3E+6
225	8473	2.61	2.44	2.23	1.94	9000	2.77	31.93	11	45.1	197	7.2E+6
	15409	4.58	4.32	3.98	3.43	16000	4.76	32.24	11	47.8	183	8.4E+6
275	8485	3.02	2.88	2.68	2.35	9000	3.20	32.76	11	53.0	124	8.6E+6
	15294	5.21	4.98	4.65	4.07	16000	5.45	32.87	11	54.3	124	9.5E+6
325	10106	2.14	2.07	1.96	1.81	9000	1.91	33.67	15	66.3	134	9.0E+6
	15771	3.67	3.57	3.39	3.13	16000	3.72	33.87	15	70.3	108	9.2E+6
375	9598	2.14	2.04	1.95	1.80	9000	2.01	33.42	15	61.9	145	7.4E+6
	15751	3.61	3.46	3.33	3.07	16000	3.67	33.67	15	66.3	123	8.3E+6
425	10623	2.00	1.93	1.81	1.72	9000	1.69	33.60	15	65.0	157	9.7E+6
	16343	3.41	3.33	3.12	2.90	16000	3.34	33.80	15	68.8	126	9.8E+6
473	8378	1.97	1.89	1.78	1.64	9000	2.12	33.35	15	60.8	143	6.8E+6
	15326	3.35	3.23	3.05	2.82	16000	3.50	33.55	15	64.0	139	8.1E+6
						average deflection at 9000 lbs	2.40		Average	53.0	188	7.7E+6
						average deflection at 16000 lbs.	4.37		Variance	140.8	6528	2.6E+12
									Std. Dev.	11.9	81	1.6E+6

average deflection at 9000 lbs	2.58	**Total Average**	**50.5**	**201**	**8.0E+6**
average deflection at 16000 lbs.	4.59	**Total Variance**	**148.1**	**8668**	**5.0E+12**
		Total Std. Dev.	**12.2**	**93**	**2.2E+6**

Load Transfer Efficiency

PCC thickness = 10" (except on Lane 1 from STA 298 to 483 where PCC thickness = 14")

Diameter of Plate = 11.8 in.
Target Load = 9000 and 16000 lbs.

Pavement Temperature (F) = 36 degrees

WB Lane 2 (South Wheel Path)

		Deflection, mils			
STA	Weight	Under load	12" behind	LTE	Crack Type
419	8501	3.12	3.01	96.5%	Tape Insert
	15330	5.33	5.15	96.6%	
Average				**96.5%**	
411	8978	3.29	3.11	94.5%	Tape Insert
	15501	5.64	5.34	94.7%	
Average				**94.6%**	
402	8342	3.19	3.00	94.0%	Tape Insert
	15290	5.47	5.19	94.9%	
Average				**94.5%**	
378	8557	3.24	3.07	94.8%	Tape Insert
	15421	5.58	5.29	94.8%	
Average				**94.8%**	
359	8346	3.11	2.98	95.8%	Tape Insert
	15362	5.43	5.18	95.4%	
Average				**95.6%**	
337	8390	3.07	2.93	95.4%	Soff-Cut
	15338	5.28	5.11	96.8%	
Average				**96.1%**	
328	8330	2.87	2.68	93.4%	Soff-Cut
	15310	5.02	4.72	94.0%	
Average				**93.7%**	
311	8354	2.77	2.59	93.5%	Soff-Cut
	15298	4.90	4.57	93.3%	
Average				**93.4%**	
284	8426	3.15	3.04	96.5%	Soff-Cut
	15231	5.46	5.26	96.3%	
Average				**96.4%**	
251	8732	2.94	2.89	98.3%	Soff-Cut
	15469	5.10	4.96	97.3%	
Average				**97.8%**	
227	8418	2.90	2.75	94.8%	Soff-Cut
	15255	5.00	4.77	95.4%	
Average				**95.1%**	
187	9204	2.46	2.19	89.0%	Soff-Cut
	15552	4.32	3.90	90.3%	
Average				**89.7%**	
159	8450	2.35	2.17	92.3%	Soff-Cut
	15219	4.22	3.94	93.4%	
Average				**92.9%**	
119	8418	2.41	2.16	89.6%	Tape Insert
	15302	4.19	3.86	92.1%	
Average				**90.9%**	
111	8263	2.44	2.21	90.6%	Tape Insert
	15179	4.35	3.94	90.6%	
Average				**90.6%**	
88	8795	3.07	2.78	90.6%	Tape Insert
	15402	5.51	5.04	91.5%	
Average				**91.0%**	
72	8346	2.85	2.72	95.4%	Tape Insert
	15235	5.12	4.88	95.3%	
Average				**95.4%**	
36	8350	2.19	2.03	92.7%	Soff-Cut
	15223	3.94	3.65	92.6%	
Average				**92.7%**	
Total Average				**94.0%**	
Variance				**0.05%**	
Standard Deviation				**2.32%**	

EB Lane 1 (North Wheel Path)

		Deflection, mils		
STA	Weight	Under load	12" behind	LTE
169	8422	2.59	2.31	89.2%
	15306	4.59	4.16	90.6%
Average				**89.9%**
174	8438	2.59	2.40	92.7%
	15147	4.59	4.26	92.8%
Average				**92.7%**
224	9633	2.69	2.48	92.2%
	15505	4.79	4.44	92.7%
Average				**92.4%**
234	9300	2.90	2.88	99.3%
	15656	5.21	5.09	97.7%
Average				**98.5%**
239	8426	3.09	2.91	94.2%
	15231	5.37	5.09	94.8%
Average				**94.5%**
253	9367	3.22	3.10	96.3%
	15004	5.93	5.63	94.9%
Average				**95.6%**
Average				**93.9%**
Variance				**0.08%**
Standard Deviation				**2.88%**

Appendix C

Technical Specs of Sensors

CONCRETE STRAIN GAGES (STATIC)

Description

The gages used correspond to the EGP-Series Embedment Strain Gage, manufactured by Micro-Measurements (Vishay Measurements Group). This type of strain gage is specially designed for measuring mechanical strains inside concrete structures. The sensing grid, constructed of a nickel-chromium alloy (similar to Karma), has an active gage length of 4 in (100 mm) for averaging strains in aggregate materials. A rugged 5-in (130-mm) outer body of polymer concrete resists mechanical damage during pouring, minimizes reinforcement of the structure, and provides protection from moisture and corrosive attack. The grid, cast within the polymer concrete to ensure maximum strain sensitivity, is self-temperature-compensated to minimize thermal output when installed in concrete structures. Each gage incorporates a heavy-duty 10-ft (3-m) cable with 22-AWG (0.643-mm diameter) leadwires; a three-wire construction to the sensing grid helps minimize temperature effects in the instrumentation leads.

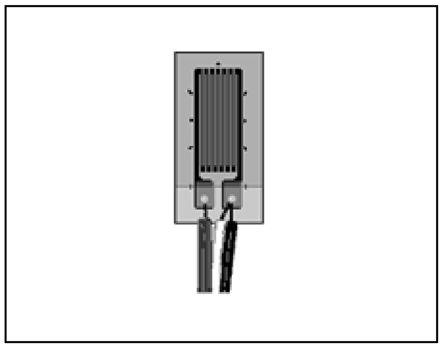
Specifications

- **Construction**. Strain sensing grid cast in a sturdy, water-resistant material.
- **Sensing Grid**. Nickel-chromium alloy on polyimide backing. Active gage length of 4 in (100 mm) nominal. Grid resistance of 120 or 350 ohms, $\pm$0.8%.
- **Outer Body**. Proprietary polymer concrete. 5 x 0.7 x 0.4 in (130 x 17 x 10 mm) nominal.
- **Cable**. Three 10-ft (3-m) leads of 22-AWG (0.643-mm dia.) stranded tinned copper in 0.015-in (0.4-mm) thick PVC insulation. Nominal cable diameter of 0.2 in (5 mm). (Other lengths quoted upon request.)
- **Temperature Range**. The normal usage range is +25 to +125 deg F (-5 to +50 deg C). Extended range is -25 to +150 deg F (-30 to +60 deg C).

REINFORCEMENT STRAIN GAGES:

Description

The gages used with the rebars correspond to the model CEA-06-250UW350, manufactured by Micro-Measurements (Vishay Measurements Group). The CEA-Series are universal general-purpose strain gages. Constantan grid completely encapsulated in polyimide, with large, rugged copper-coated tabs. Primarily used for general-purpose static and dynamic stress analysis. The gages were ordered with preattached leadwire cables.



Specifications

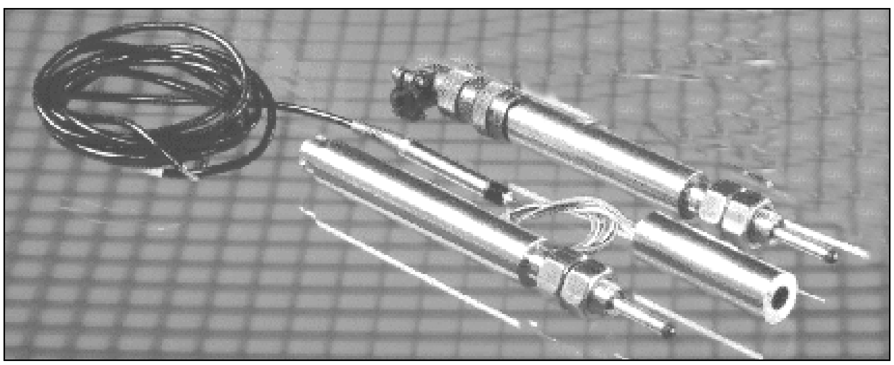
- **Temperature Range**: Normal: -100 deg to +350 deg F (-75 deg to +175 deg C). Special or Short-Term: -320 deg to +400 deg F (-195 to +205 C)
- **Strain Range:** ±3% for gage lengths under 1/8 in (3.2mm)±5% for 1/8 in and over
- **Fatigue Life**: 10^5 cycles at +1500 microstrain / 10^6 cycles at +1500 microstrain with low modulus solder.
- **Dimensions**

	in	mm
Gage Length	0.250	6.35
Overall Length	0.45	11.43
Grid Width	0.180	4.57
Overall Width	0.180	4.57
Matrix Length	0.55	14.0
Matrix Width	0.27	6.9

LINEAR VARIABLE DIFFERENTIAL TRANSFORMERS (LVDTs)

Description

The vertical LVDTs correspond to model HSA 750-250 and the horizontal LVDTs are GHSA 750-125, both models manufactured by MacroSensors.
The HSA and GHSA series are specifically designed for use in wet and/or dirty environments. They feature a welded, hermetically sealed stainless steel shell. They are available in either AC or DC, but AC operated units are recommended for applications where the temperature or temperature variation at the location of the sensor is severe and not suited for integral electronics. All the LVDTs employed in this project are with AC signal. The signal conditioner for the static system comes from Macrosensors. It is the LPC-2000 Line Powered Conditioner. It runs on 110 AC, which it converts to 3kHz, 3 Vrms for the LVDTs, and then returns a $\pm$10VDC signal for the Dataloggers. The conditioners are set up in master-slave mode to synchronize the AC signal to minimize "crosstalk" or signal noise between the LVDT cables. Basically one conditioner is configured as the "master" and the rest of the conditioners in the groups are the "slaves" and thus are in phase with the master.



Specifications HSA 750-250 model:

GENERAL SPECIFICATIONS

Input:	3.0 V, 2.5k Hz
Operating Temperature Range:	-65° to +221° F
Operating Temperature Range:	-54° to +105° C
Core-To-Bore Clearance:	0.024 Inch (Radial)
Core-To-Bore Clearance:	0.60 Millimeter (Radial)
Null Voltage:	Less Than 0.5% FSO
Vibration Tolerance:	20g to 2k Hz
Shock Survival:	500g, 11ms
Housing Material:	400 Series Stainless Steel
Environmental Seal:	All Welded, Hermetically Sealed

UNIT SPECIFICATIONS

PARAMETER	UNIT OF MEASURE	HSA 750-250
Stroke	Inches	±0.250
Non-Linearity	Plus/Minus %	0.25%
Sensitivity	mV/V/.001 Inch	2.4
Phase Shift	Degrees	-8.4
Primary Impedence	Ohms	1400
Secondary Impedence	Ohms	3550
Body Length ("A")	Inches	3.39
Core Length ("B")	Inches	1.65
Null Position	Inches	1.32
Weight Body	Ounces	2.5
Weight Core	Ounces	0.18

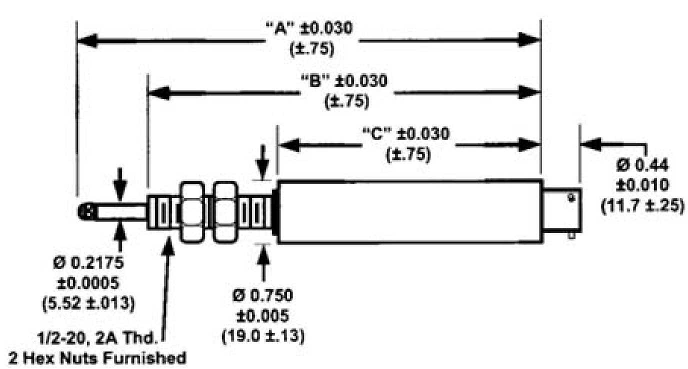
Specifications GHAS 750-125 model:

GENERAL SPECIFICATIONS

PARAMETER	SPECIFICATION
Input Voltage:	3 V rms.
Input Frequency:	3.0 kHz
Null Voltage:	Less than 0.5% of FSO
Non-Linearity:	±0.25% of FRO
Repeatability:	0.000025 inch (0.0006 mm)
Operating Temperature Range:	-65 °F to +220 °F (-55 °C to +105 °C)
Temperature Coefficient of Sensitivity:	0.01% of FSO/°F (0.018% of FSO/°C)

UNIT SPECIFICATIONS

PARAMETER	UNIT OF MEASURE	GHSA 750-125
Measurement Range	Inches	±0.125
Pretravel*	Inches	0.13
Overtravel*	Inches	0.13
Spring Load Over Range	Ounces	3.4 to 5.7
Sensitivity	mV/V/.001 Inch	3.9
Weight	Ounces	3.4
Dimension A	Inches	5.30
Dimension B	Inches	4.19
Dimension C	Inches	2.64



CONCRETE STRAIN GAGES (DYNAMIC)

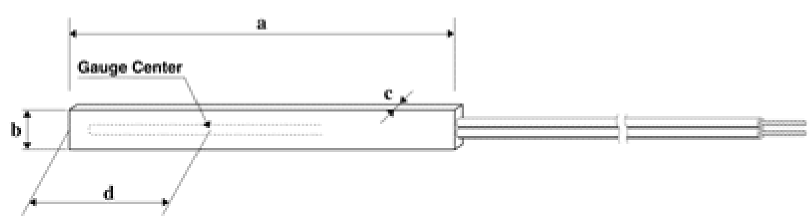
Description

These gages are the model PML-60-2L fabricated by Tokyo Sokki Kenkyujo CO. These sensors are specially designed for measuring interior strain in concrete and mortar under a loading test. The PM is sealed between thin resin plates, and the PMF employs super engineering plastics capable of superior water-proofing characteristics.

Specifications

- Main Test Materials: Concrete Mortar
- Operating Temperature: -20 to +60°C
- Materials Backing: Acrylic(PM) Special plastics(PMF
- Materials Element: Cu-Ni alloy wire(PM) Cu-Ni alloy foil (PMF)
- Strain limit: 2% (20000×10-6)
- Single element(G.F. 2.1 approx.) :0.3mm2 heat resistive vinyl leadwire 2m pre-attached
- Dimensions

Type	Gauge length (mm)	Gauge width (mm)	Backing length a(mm)	Backing width b(mm)	Backing thickness c(mm)	d(mm)	Resistance (Ω)
PML-60-2L	60	1	125	13	5	40	120



Appendix D

Programs for the Dataloggers

The following text is the program written using the PC208W Datalogger Support Software for the system in Lane 1. The system in Lane 2 uses an almost identical program, and the weather station utilizes a program that follows the same format.

```
;{CR10X}
;
;  DATALOGGER BOX 1
;
*Table 1 Program
 01: 60       Execution Interval
(seconds)

1:  Batt Voltage (P10)
 1: 1       Loc [ Battery   ]

;                                   ----
Set type of ports
2:  Set Port(s) (P20)
 1: 4444    C8..C5 =
10ms/10ms/10ms/10ms
 2: 3344    C4..C1 =
1ms/1ms/10ms/10ms

;              C1=CLK in M3
C2=CLK in M3   C3=CLK in T
C4=RES in T
;              C5=RES in M1
C6=CLK in M1   C7=CLK in M2
C8=RES in M2

;---Strain Gage Measurement--
; --- Set zero for all the strain gages

3:  If Flag/Port (P91)
 1: 21      Do if Flag 1 is Low
 2: 1       Call Subroutine 1

; --- Activate M1

4:  Do (P86)
 1: 45      Set Port 5 High

5:  Beginning of Loop (P87)
 1: 0       Delay
 2: 16      Loop Count

   6:  Do (P86)
    1: 76      Pulse Port 6

   7:  Excitation with Delay (P22)
    1: 3       Ex Channel
    2: 0       Delay W/Ex (units =
0.01 sec)
    3: 20      Delay After Ex (units
= 0.01 sec)
    4: 0       mV Excitation

   8:  Full Bridge (P6)
    1: 1       Reps
    2: 3       25 mV Slow Range
    3: 6       DIFF Channel
    4: 3       Excite all reps
w/Exchan 3
    5: 2500    mV Excitation
    6: 60   -- Loc [ M1mv_1    ]
    7: 1       Mult
    8: 0.0     Offset

9:  End (P95)

10:  Do (P86)
 1: 55      Set Port 5 Low

;  ---- Activate M2

11:  Do (P86)
 1: 48      Set Port 8 High

12:  Beginning of Loop (P87)
 1: 0       Delay
 2: 16      Loop Count

   13:  Do (P86)
    1: 77      Pulse Port 7

   14:  Excitation with Delay (P22)
    1: 3       Ex Channel
    2: 0       Delay W/Ex (units =
0.01 sec)
    3: 20      Delay After Ex (units
= 0.01 sec)
    4: 0       mV Excitation

   15:  Full Bridge (P6)
    1: 1       Reps
    2: 3       25 mV Slow Range
    3: 4       DIFF Channel
    4: 3       Excite all reps
w/Exchan 3
    5: 2500    mV Excitation
    6: 76   -- Loc [ M2mv_1    ]
    7: 1       Mult
    8: 0.0     Offset

16:  End (P95)

17:  Do (P86)
 1: 58      Set Port 8 Low

; ---- Activate M3

18:  Do (P86)
 1: 41      Set Port 1 High

19:  Beginning of Loop (P87)
 1: 0       Delay
 2: 16      Loop Count

   20:  Do (P86)
    1: 72      Pulse Port 2

   21:  Excitation with Delay (P22)
    1: 3       Ex Channel
    2: 0       Delay W/Ex (units =
0.01 sec)
    3: 20      Delay After Ex (units =
0.01 sec)
    4: 0       mV Excitation

   22:  Full Bridge (P6)
    1: 1       Reps
    2: 3       25 mV Slow Range
    3: 5       DIFF Channel
    4: 3       Excite all reps w/Exchan
3
    5: 2500    mV Excitation
    6: 92   -- Loc [ M3mv_1    ]
    7: 1       Mult
    8: 0.0     Offset

23:  End (P95)

24:  Do (P86)
 1: 51      Set Port 1 Low

;  ---- SG1

25:  Excitation with Delay (P22)
 1: 2       Ex Channel
 2: 0       Delay W/Ex (units = 0.01
sec)
 3: 10      Delay After Ex (units =
0.01 sec)
```

```
 4: 0       mV Excitation

26:  Full Bridge (P6)
 1: 1       Reps
 2: 3       25 mV Slow Range
 3: 2       DIFF Channel
 4: 2       Excite all reps w/Exchan
2
 5: 2500    mV Excitation
 6: 108     Loc [ SG1mv     ]
 7: 1       Mult
 8: 0.0     Offset
;   ---- SG2

27:  Excitation with Delay (P22)
 1: 2       Ex Channel
 2: 0       Delay W/Ex (units = 0.01
sec)
 3: 10      Delay After Ex (units =
0.01 sec)
 4: 0       mV Excitation

28:  Full Bridge (P6)
 1: 1       Reps
 2: 3       25 mV Slow Range
 3: 3       DIFF Channel
 4: 2       Excite all reps w/Exchan
2
 5: 2500    mV Excitation
 6: 109     Loc [ SG2mv     ]
 7: 1       Mult
 8: 0.0     Offset

;  ---- Calculate strain
;  ---- M1
29:  Beginning of Loop (P87)
 1: 0       Delay
 2: 16      Loop Count

    30:  Z=X-Y (P35)
     1: 60    -- X Loc [ M1mv_1    ]
     2: 10    -- Y Loc [ M1zero_1  ]
     3: 7       Z Loc [ Vr       ]

    ;Convert milivolts to volts
    31:  Z=X*F (P37)
     1: 7       X Loc [ Vr       ]
     2: 0.001    F
     3: 7       Z Loc [ Vr       ]

    32:  Z=X*F (P37)
     1: 7       X Loc [ Vr       ]
     2: -2      F
     3: 9       Z Loc [ _12Vr____ ]

    33:  Z=Z+1 (P32)
     1: 9       Z Loc [ _12Vr____ ]

    34:  Z=X/Y (P38)
     1: 7       X Loc [ Vr       ]
     2: 9       Y Loc [ _12Vr____ ]
     3: 8       Z Loc [ Vr_12Vr  ]

    35:  Z=X*Y (P36)
     1: 8       X Loc [ Vr_12Vr  ]
     2: 6       Y Loc [ Mult     ]
     3: 110   -- Z Loc [ M1str_1  ]

36:  End (P95)

;    ---- M2
; ---- Embedded gages (concrete)
37:  Beginning of Loop (P87)
 1: 0       Delay
 2: 14      Loop Count

    38:  Z=X-Y (P35)
     1: 76    -- X Loc [ M2mv_1    ]
     2: 26    -- Y Loc [ M2zero_1  ]
     3: 7       Z Loc [ Vr       ]

    ;Convert milivolts to volts
    39:  Z=X*F (P37)
     1: 7       X Loc [ Vr       ]
     2: 0.001    F
     3: 7       Z Loc [ Vr       ]

    40:  Z=X*F (P37)
     1: 7       X Loc [ Vr       ]
     2: -2      F
     3: 9       Z Loc [ _12Vr____ ]

    41:  Z=Z+1 (P32)
     1: 9       Z Loc [ _12Vr____ ]

    42:  Z=X/Y (P38)
     1: 7       X Loc [ Vr       ]
     2: 9       Y Loc [ _12Vr____ ]
     3: 8       Z Loc [ Vr_12Vr  ]

    43:  Z=X*Y (P36)
     1: 8       X Loc [ Vr_12Vr  ]
     2: 6       Y Loc [ Mult     ]
     3: 126   -- Z Loc [ M2str_1  ]

44:  End (P95)
;    ---- Foil gages (rebars)

45:  Beginning of Loop (P87)
 1: 0       Delay
 2: 2       Loop Count

    46:  Z=X-Y (P35)
     1: 90    -- X Loc [ M2mv_15   ]
     2: 40    -- Y Loc [ M2zero_15 ]
     3: 7       Z Loc [ Vr       ]

    ;Convert milivolts to volts
    47:  Z=X*F (P37)
     1: 7       X Loc [ Vr       ]
     2: 0.001    F
     3: 7       Z Loc [ Vr       ]

    48:  Z=X*F (P37)
     1: 7       X Loc [ Vr       ]
     2: -2      F
     3: 9       Z Loc [ _12Vr____ ]

    49:  Z=Z+1 (P32)
     1: 9       Z Loc [ _12Vr____ ]

    50:  Z=X/Y (P38)
     1: 7       X Loc [ Vr       ]
     2: 9       Y Loc [ _12Vr____ ]
     3: 8       Z Loc [ Vr_12Vr  ]

    51:  Z=X*Y (P36)
     1: 8       X Loc [ Vr_12Vr  ]
     2: 5       Y Loc [ Mult2    ]
     3: 140   -- Z Loc [ M2str_15  ]

52:  End (P95)

;    ---- M3
53:  Beginning of Loop (P87)
 1: 0       Delay
 2: 16      Loop Count

    54:  Z=X-Y (P35)
     1: 92    -- X Loc [ M3mv_1    ]
     2: 42    -- Y Loc [ M3zero_1  ]
     3: 7       Z Loc [ Vr       ]

    ;Convert milivolts to volts
    55:  Z=X*F (P37)
     1: 7       X Loc [ Vr       ]
     2: 0.001    F
     3: 7       Z Loc [ Vr       ]

    56:  Z=X*F (P37)
     1: 7       X Loc [ Vr       ]
     2: -2      F
     3: 9       Z Loc [ _12Vr____ ]

    57:  Z=Z+1 (P32)
     1: 9       Z Loc [ _12Vr____ ]

    58:  Z=X/Y (P38)
```

```
      1: 7        X Loc [ Vr        ]
      2: 9        Y Loc [ _12Vr____ ]
      3: 8        Z Loc [ Vr_12Vr   ]

   59:  Z=X*Y (P36)
      1: 8        X Loc [ Vr_12Vr   ]
      2: 5        Y Loc [ Mult2     ]
      3: 142   -- Z Loc [ M3str_1   ]

60:  End (P95) ;

;  ---- SG1

61:  Z=X-Y (P35)
 1: 108      X Loc [ SG1mv     ]
 2: 58       Y Loc [ SG1zero   ]
 3: 7        Z Loc [ Vr        ]

   ;Convert milivolts to volts
62:  Z=X*F (P37)
 1: 7        X Loc [ Vr        ]
 2: 0.001    F
 3: 7        Z Loc [ Vr        ]

63:  Z=X*F (P37)
 1: 7        X Loc [ Vr        ]
 2: -2       F
 3: 9        Z Loc [ _12Vr____ ]

64:  Z=Z+1 (P32)
 1: 9        Z Loc [ _12Vr____ ]

65:  Z=X/Y (P38)
 1: 7        X Loc [ Vr        ]
 2: 9        Y Loc [ _12Vr____ ]
 3: 8        Z Loc [ Vr_12Vr   ]

66:  Z=X*Y (P36)
 1: 8        X Loc [ Vr_12Vr   ]
 2: 5        Y Loc [ Mult2     ]
 3: 158      Z Loc [ SG1str    ]

;---- SG2

67:  Z=X-Y (P35)
 1: 109      X Loc [ SG2mv     ]
 2: 59       Y Loc [ SG2zero   ]
 3: 7        Z Loc [ Vr        ]

   ;Convert milivolts to volts
68:  Z=X*F (P37)
 1: 7        X Loc [ Vr        ]
 2: 0.001    F
 3: 7        Z Loc [ Vr        ]

69:  Z=X*F (P37)
 1: 7        X Loc [ Vr        ]
 2: -2       F
 3: 9        Z Loc [ _12Vr____ ]

70:  Z=Z+1 (P32)
 1: 9        Z Loc [ _12Vr____ ]

71:  Z=X/Y (P38)
 1: 7        X Loc [ Vr        ]
 2: 9        Y Loc [ _12Vr____ ]
 3: 8        Z Loc [ Vr_12Vr   ]

72:  Z=X*Y (P36)
 1: 8        X Loc [ Vr_12Vr   ]
 2: 5        Y Loc [ Mult2     ]
 3: 159      Z Loc [ SG2str    ]
;     ---- Write Strain Output
73:  Do (P86)
 1: 10       Set Output Flag High
(Flag 0)

74:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 2        Array ID

75:  Real Time (P77)
 1: 110      Day,Hour/Minute
(midnight = 0000)

76:  Sample (P70)
 1: 50       Reps
 2: 110      Loc [ M1str_1   ]


;Thermocouple Measurement---
; ---- Activate T

77:  Do (P86)
 1: 44       Set Port 4 High

78:  Internal Temperature (P17)
 1: 160      Loc [ IntRef    ]

79:  Full Bridge (P6)
 1: 1        Reps
 2: 23       25 mV 60 Hz Rejection
Range ;
 3: 1        DIFF Channel
 4: 1        Excite all reps w/Exchan
1
 5: 1200     mV Excitation
 6: 161      Loc [ RefTemp_C ]
 7: -0.001   Mult
 8: 0.09707  Offset

;    ---- Calculate reference resistance
80:  BR Transform Rf[X/(1-X)] (P59)
 1: 1        Reps
 2: 161      Loc [ RefTemp_C ]
 3: 10.025   Multiplier (Rf)
;  ---- Calculate reference temperature
81:  Temperature RTD (P16)
 1: 1        Reps
 2: 161      R/R0 Loc [ RefTemp_C ]
 3: 161      Loc [ RefTemp_C ]
 4: 1.0      Mult
 5: 0.0      Offset
;   ---- Loop T
82:  Beginning of Loop (P87)
 1: 0        Delay
 2: 25       Loop Count

    83:  Do (P86)
     1: 73       Pulse Port 3

    84:  Do (P86)
     1: 73       Pulse Port 3

    85:  Thermocouple Temp (DIFF)
(P14)
     1: 1        Reps
     2: 21       2.5 mV 60 Hz Rejection
Range
     3: 1        DIFF Channel
     4: 1        Type T (Copper-
Constantan)
     5: 161      Ref Temp (Deg. C) Loc
[ RefTemp_C ]
     6: 162   -- Loc [ TC_1      ]
     7: 1.0      Mult
     8: 0.0      Offset

86:  End (P95)
;        ---- End loop T
;          ---- Deactivate T

87:  Do (P86)
 1: 54       Set Port 4 Low

;      ----Write Thermocouple Output

88:  Do (P86)
 1: 10       Set Output Flag High (Flag
0)

89:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 3        Array ID

90:  Real Time (P77)
```

```
 1: 110      Day,Hour/Minute
(midnight = 0000)

91:  Sample (P70)
 1: 1        Reps
 2: 1     -- Loc [ Battery   ]

92:  Sample (P70)
 1: 1        Reps
 2: 161      Loc [ RefTemp_C ]

93:  Sample (P70)
 1: 1        Reps
 2: 160      Loc [ IntRef    ]

94:  Sample (P70)
 1: 25       Reps
 2: 162   -- Loc [ TC_1      ]


*Table 2 Program
  02: 0.0000    Execution Interval
(seconds)


*Table 3 Subroutines

;---------------------- Subroutine to
measure initial (unloaded) Vo in
each strain gage---------------------
1:  Beginning of Subroutine (P85)
 1: 1        Subroutine 1

    2:  Z=F (P30)
     1: 4        F
     2: 6        Exponent of 10
     3: 2        Z Loc [ _4e6_____ ]

    3:  Z=F (P30)
     1: 2.06     F
     2: 00       Exponent of 10
     3: 4        Z Loc [ GF        ]

    4:  Z=F (P30)
     1: 2.09     F
     2: 00       Exponent of 10
     3: 3        Z Loc [ GF2       ]

    5:  Z=X/Y (P38)
     1: 2        X Loc [ _4e6_____ ]
     2: 4        Y Loc [ GF        ]
     3: 6        Z Loc [ Mult      ]

    6:  Z=X/Y (P38)
     1: 2        X Loc [ _4e6_____ ]
     2: 3        Y Loc [ GF2       ]
     3: 5        Z Loc [ Mult2     ]

;   ---- Activate M1
    7:  Do (P86)
     1: 45       Set Port 5 High

    8:  Beginning of Loop (P87)
     1: 0        Delay
     2: 16       Loop Count

        9:  Do (P86)
         1: 76       Pulse Port 6

        10:  Excitation with Delay
(P22)
         1: 3        Ex Channel
         2: 0        Delay W/Ex (units
= 0.01 sec)
         3: 20       Delay After Ex
(units = 0.01 sec)
         4: 0        mV Excitation

        11:  Full Bridge (P6)
         1: 1        Reps
         2: 3        25 mV Slow Range
         3: 6        DIFF Channel
         4: 3        Excite all reps
w/Exchan 3
         5: 2500     mV Excitation
         6: 10    -- Loc [ M1zero_1  ]
         7: 1        Mult
         8: 0.0      Offset

    12:  End (P95)

13:  Do (P86)
 1: 55       Set Port 5 Low

;      ---- Activate M2
    14:  Do (P86)
     1: 48       Set Port 8 High

    15:  Beginning of Loop (P87)
     1: 0        Delay
     2: 16       Loop Count

        16:  Do (P86)
         1: 77       Pulse Port 7

        17:  Excitation with Delay
(P22)
         1: 3        Ex Channel
         2: 0        Delay W/Ex (units
= 0.01 sec)
         3: 20       Delay After Ex
(units = 0.01 sec)
         4: 0        mV Excitation

        18:  Full Bridge (P6)
         1: 1        Reps
         2: 3        25 mV Slow Range
         3: 4        DIFF Channel
         4: 3        Excite all reps
w/Exchan 3
         5: 2500     mV Excitation
         6: 26    -- Loc [ M2zero_1  ]
         7: 1        Mult
         8: 0.0      Offset

    19:  End (P95)

20:  Do (P86)
 1: 58       Set Port 8 Low

;    ---- Activate M3
    21:  Do (P86)
     1: 41       Set Port 1 High

    22:  Beginning of Loop (P87)
     1: 0        Delay
     2: 16       Loop Count

        23:  Do (P86)
         1: 72       Pulse Port 2

        24:  Excitation with Delay
(P22)
         1: 3        Ex Channel
         2: 0        Delay W/Ex (units =
0.01 sec)
         3: 20       Delay After Ex (units
= 0.01 sec)
         4: 0        mV Excitation

        25:  Full Bridge (P6)
         1: 1        Reps
         2: 3        25 mV Slow Range
         3: 5        DIFF Channel
         4: 3        Excite all reps
w/Exchan 3
         5: 2500     mV Excitation
         6: 42    -- Loc [ M3zero_1  ]
         7: 1        Mult
         8: 0.0      Offset

    26:  End (P95)

27:  Do (P86)
 1: 51       Set Port 1 Low

;       ---- SG1
```

28: Excitation with Delay (P22)
1: 2   Ex Channel
2: 0   Delay W/Ex (units = 0.01 sec)
3: 10   Delay After Ex (units = 0.01 sec)
4: 0   mV Excitation

29: Full Bridge (P6)
1: 1   Reps
2: 3   25 mV Slow Range
3: 2   DIFF Channel
4: 2   Excite all reps w/Exchan 2
5: 2500   mV Excitation
6: 58   Loc [SG1zero   ]
7: 1   Mult
8: 0.0   Offset

;   ---- SG2

30: Excitation with Delay (P22)
1: 2   Ex Channel
2: 0   Delay W/Ex (units = 0.01 sec)
3: 10   Delay After Ex (units = 0.01 sec)
4: 0   mV Excitation

31: Full Bridge (P6)
1: 1   Reps
2: 3   25 mV Slow Range
3: 3   DIFF Channel
4: 2   Excite all reps w/Exchan 2
5: 2500   mV Excitation
6: 59   Loc [SG2zero   ]
7: 1   Mult
8: 0.0   Offset

;   ---- Write initial zero for s.g.

32: Do (P86)
1: 10   Set Output Flag High (Flag 0)

33: Set Active Storage Area (P80)
1: 1   Final Storage Area 1
2: 1   Array ID

34: Real Time (P77)
1: 110   Day,Hour/Minute (midnight = 0000)

35: Sample (P70)
1: 50   Reps
2: 10   Loc [M1zero_1]

; ---- Indicate that the zero reading has been taken

36: Do (P86)
1: 11   Set Flag 1 High

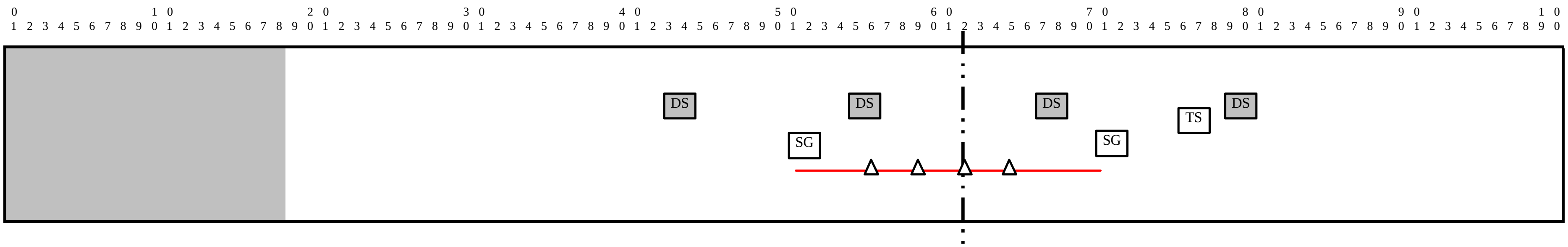
37: End (P95)

End Program

Appendix E

Location of Sensors

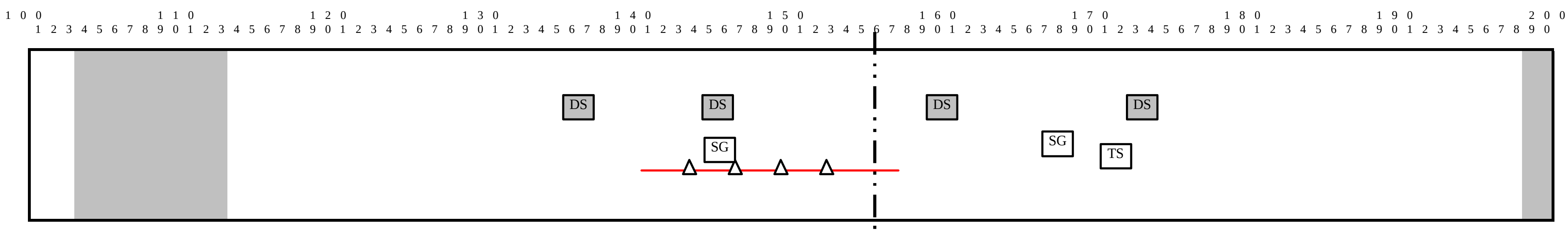
Section 1



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
42.9 , 4.40	51.0	55.7	77.0
54.9 , 4.55	71.6	58.5	
66.8 , 4.50		61.4	
78.8 , 4.50		64.5	

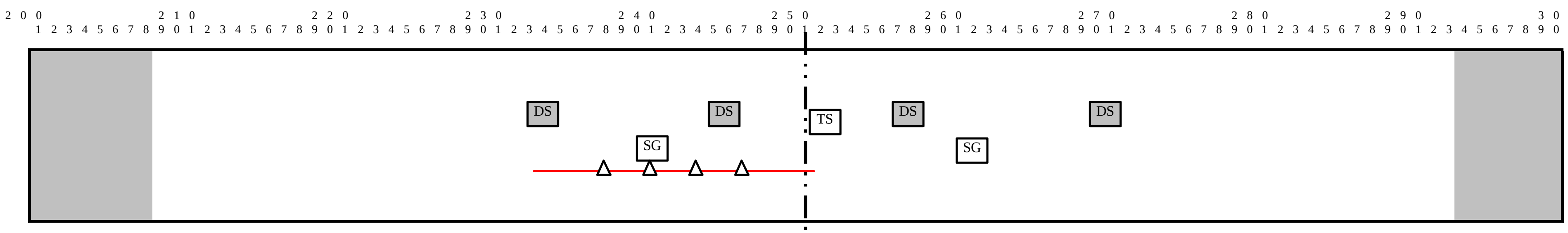
Section 2



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
135.0 , 4.50	145.1	143.3	172.1
145.0 , 4.15	167.5	146.3	
160.9 , 4.50		149.3	
173.3 , 4.50		152.1	

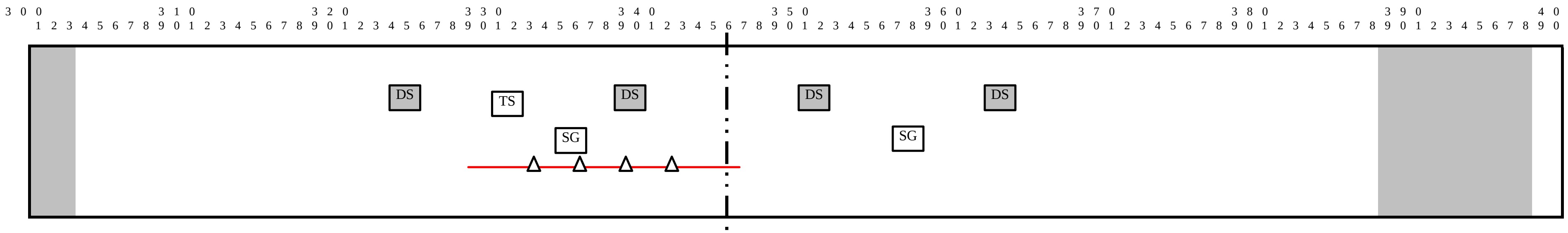
Section 3



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
233.4 , 4.50	240.4	237.6	251.4
245.3 , 4.60	261.3	240.7	
257.2 , 4.50		243.7	
270.6 , 4.45		246.7	

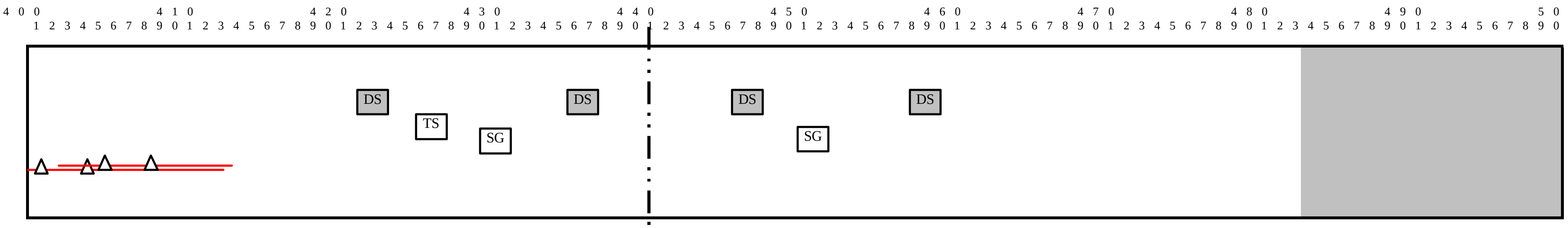
Section 4



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
324.0 , 4.40	335.2	333.0	330.8
339.2 , 4.40	357.2	335.9	
351.2 , 4.40		338.8	
363.2 , 4.50		341.8	

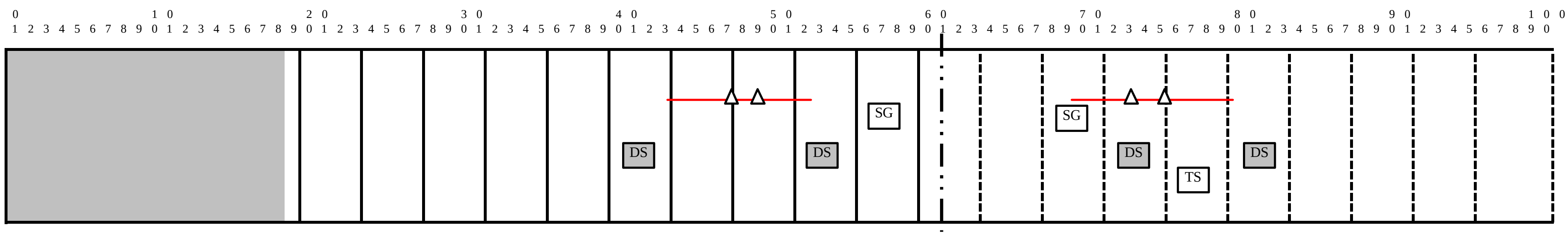
Section 5



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
422.5 , 4.45	429.0	400.4	426.6
436.7 , 4.45	451.5	403.4	
447.3 , 4.50		405.0	
458.7 , 4.55		408.1	

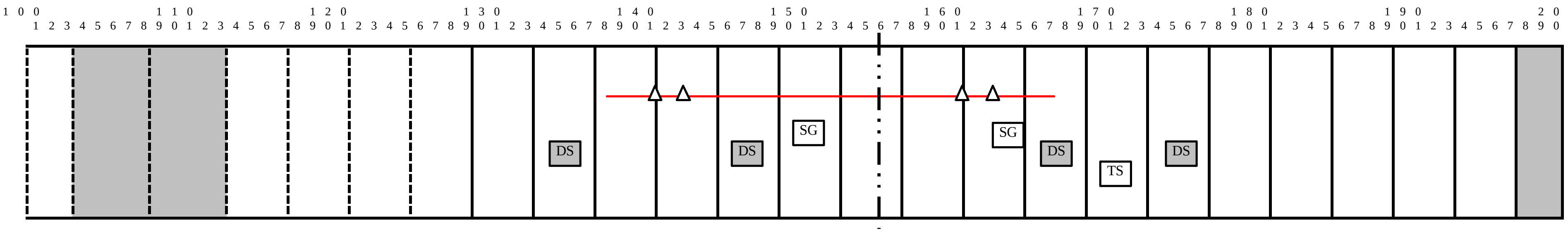
Section 6



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
41.0 , 4.50	57.0	47.0	77.0
54.0 , 4.50	68.4	49.0	
59.0 , 4.50		73.0	
81.0 , 4.50		75.0	

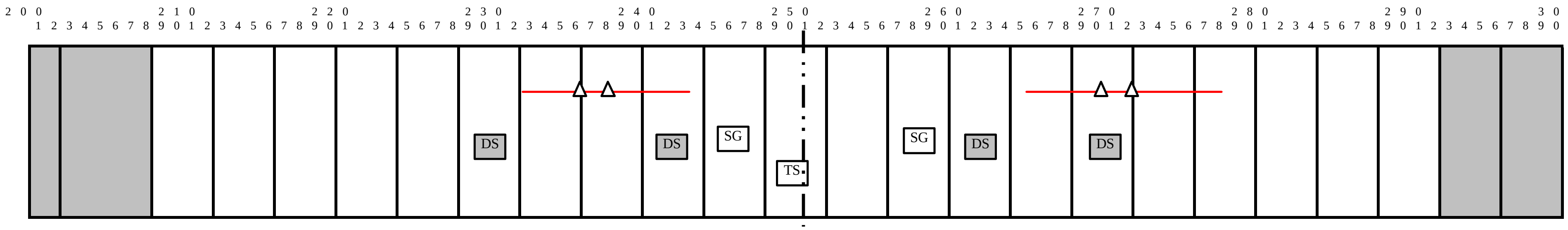
Section 7



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
135.0 , 4.50	150.5	141.0	170.0
148.0 , 4.50	164.6	143.0	
167.0 , 4.50		161.0	
175.0 , 4.50		163.0	

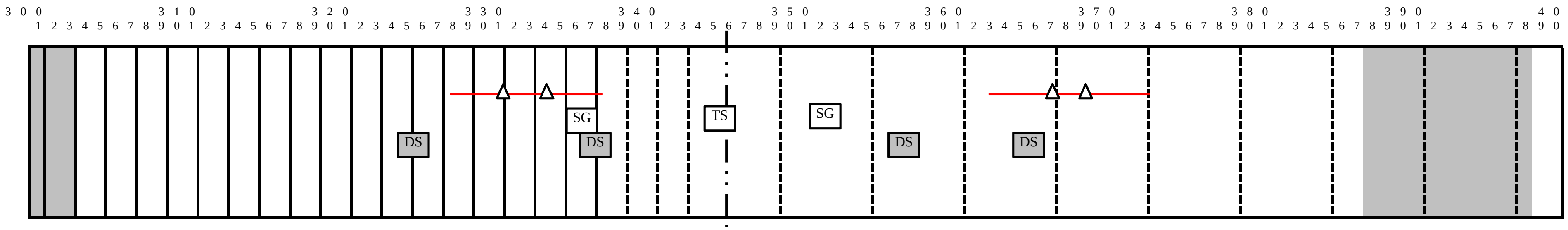
Section 8



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
230.0 , 4.50	245.2	236.0	250.0
243.0 , 4.50	257.3	238.0	
262.0 , 4.50		270.0	
270.0 , 4.50		272.0	

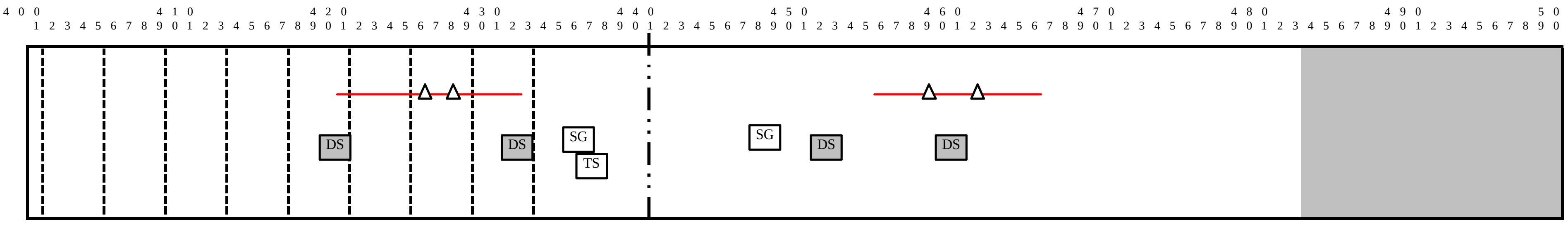
Section 9



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
326.0 , 4.50	336.0	331.0	345.0
338.0 , 4.50	351.0	334.0	
358.0 , 4.50		367.0	
365.0 , 4.50		369.0	

Section 10



Location of sensors (ft)

Dynamic	Static	Steel	Therm.
420.0 , 4.50	435.5	426.0	436.0
433.0 , 4.50	448.0	428.0	
453.0 , 4.50		459.0	
460.0 , 4.50		462.0	